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GEOLOGICAL SURVEY

PROCEEDINGS OF CONFERENCE XX

A WORKSHOP ON "THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE AND ITS IMPLICATIONS FOR TODAY"

MAY 23-26, 1983
CHALRESTON, SOUTH CAROLINA

CONVENED UNDER AUSPICES OF
NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM

SPONSORED BY

U.S. GEOLOGICAL SURVEY, NUCLEAR REGULATORY COMMISSION,
FEDERAL EMERGENCY MANAGEMENT AGENCY, NATIONAL SCIENCE FOUNDATION,
NATIONAL BUREAU OF STANDARDS, THE CITY OF CHARLESTON, AND
THE CHARLESTON, BERKELEY, AND DORCHESTER COUNTIES COUNCIL OF GOVERNMENTS

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by

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INTRODUCTION

The workshop, "The 1886 Charleston, South Carolina, Earthquake and Its Implications for Today," was held in Charleston, South Carolina, on May 23-26, 1983. The U.S. Geological Survey (USGS) joined with Nuclear Regulatory Commission (NRC), Federal Emergency Management Agency (FEMA), National Science Foundation (NSF), National Bureau of Standards (NBS), the City of Charleston, the Charleston, Berkeley, and Dorchester Counties Council of Governments, and the South Carolina Seismic Safety Consortium (SCSSC) to sponsor the workshop.

As is well known, Charleston, South Carolina, experienced a major earthquake on August 31, 1886, which caused 60 deaths, extensive damage, and widespread social and economic disruption. The earthquake, which had an estimated magnitude of 7.5 (m_s 7.5 and m_b 6.6) and an epicentral intensity of X on the Modified Mercalli Intensity Scale, was felt over a large part of the Eastern United States. During the next 30 years more than 400 aftershock occurred in the Charleston region, adding to the damage and social disruption. The region continues to experience low-level seismic activity today.

This workshop was the twentieth in a series of workshops and conferences that USGS has sponsored since 1977, usually in cooperation with one or more other agencies or institutions. Each workshop and conference has the general goal of improving knowledge utilization by bringing together knowledge producers and users. For each workshop or conference, a steering committee is created to tailor the objectives to the geographic region and to foster a process that counteracts the criticism that much of the knowledge produced through research is not fully utilized. Inadequate utilization of research occurs because of either the lack of a process which links knowledge producers and users, sometimes referred to as a network, or because of inefficient use of a network.

One hundred-fifty people having varied backgrounds in earth science, social science, architecture, engineering, and emergency management participated in the workshop on "The 1886 Charleston Earthquake and Its Implications for Today." They represented local, State, and Federal Government, industry, architectural and engineering firms, academia, and voluntary agencies. Most came from the Eastern United States (see Appendix A of the report for a list of participants).

OBJECTIVES OF THE WORKSHOP

This workshop is the third in a subseries specifically designed to define the earthquake threat in the Eastern United States and to improve earthquake preparedness. The two prior workshops on earthquake preparedness were sponsored by USGS and FEMA and brought together producers and users of hazards information with the goal of fostering partnerships. The first workshop, "Preparing for and Responding to a Damaging Earthquake in the Eastern United States," was held in Knoxville, Tennessee, in September 1981. The Knoxville workshop (described in USGS Open-File Report 82-220) demonstrated that policymakers and members of the scientific-engineering community can assimilate a great deal of technical information about earthquake hazards and work together to devise practical work plans. The workshop resulted in the creation of a draft 5-year work plan to improve the state-of-earthquake-preparedness in the Eastern United States and marked the birth of the South Carolina Seismic Safety Consortium. The second workshop, "Continuing Actions to Reduce Losses from Earthquakes in the Mississippi Valley Area," was held in St. Louis, Missouri, in May 1982. It resulted in the identification of specific actions with a high potential for reducing losses that could be implemented immediately. The results of the workshop (described in USGS Open-File Report 83-157) reaffirmed that pratical work plans can be created efficiently by a diverse group.

The Charleston workshop had multiple objectives involving the discussion of scientific information and its use in earthquake preparedness. They are:

1) To define the state-of-knowledge about geologic, engineering, and societal aspects of the 1886 Charleston earthquake.

2) To identify what is known about the 1886 Charleston earthquake in the context of eastern seismicity.

3) To recommend specific actions concerning future research, earthquake-resistant-design of buildings and critical facilities, and earthquake preparedness.

4) To identify resources for carrying out the recommendations.

A DECADE OF RESEARCH IN THE CHARLESTON REGION

Unlike the Knoxville and St. Louis workshops, the Charleston workshop was designed to communicate scientific information gained from a decade of multidisciplinary studies funded primarily by USGS and NRC in the Charleston region. Four conclusions were emphasized at the workshop:

1) No geologic structure or feature can be identified unequiviocally as the source of the 1886 Charleston earthquake.

2) Sufficient high-quality scientific information is now available as a result of a decade of research to impose physical constraints, to advance physically reasonable hypotheses for tectonic models, and to define and prioritize specific problems warranting research.

3) Seismic engineering parameters of critical facilities in the Charleston area should be determined on the basis that earthquakes similar to the 1886 Charleston earthquake have the potential to recur in the vicinity of Charleston.

4) Results of research in the Eastern United States indicate that the general geologic structures of the Charleston region can be found at other locales within the eastern seaboard (Appalachian Piedmont, Atlantic Coastal Plain, and Atlantic Contential Shelf). Discussions in some of the workshop sessions were based on the USGS position (specified in the letter from Jim Devine (USGS) on November 18, 1982, to Robert Jackson (NRC)) that although there is no recent or historical evidence that these locales have experienced strong earthquakes, the historical record is not, of itself, sufficient grounds for ruling out the occurrence at these locales of strong earthquake ground motions similar to that experienced near Charleston in 1886.

WORKSHOP PROCEDURES

The procedures used in the workshop were designed to enhance the interaction between all participants and to facilitate achievement of the objectives. The following procedures were used:

PROCEDURE 1: Research reports (listed below) and preliminary papers were distributed to each participant at the workshop and used as basic references. The reports included:

a) USGS Professional Paper 1028, "Studies Related to the Charleston, South Carolina, Earthquake of 1886--a Preliminary Report."

b) USGS Professional Paper 1313, "Studies Related to the Charleston, South Carolina, Earthquake of 1886--Tectonics and Seismicity" (note: this report was published two weeks before the workshop).

c) USGS Professional Paper 1236, "Investigations of the New Madrid, Missouri, Earthquake Region."

d) USGS Professional Paper 1240-B "Facing Geologic and

e) USGS Open-File Report 82-220, "Proceedings of the Workshop on Preparing For and Responding to a Damaging Earthquake in the Eastern United States."

f) USGS Open-File Report 83-157, "Proceedings of the Workshop on Continuing Actions to Reduce Losses from Earthquakes in the Mississippi Valley Area."

The technical papers were finalzed after the workshop and are contained in Part II of this publication.

PROCEDURE 2: Scientists, social scientists, engineers, and emergency management specialists gave oral presentation in ten plenary sessions.

The objectives were to integrate research--hazard awareness--preparedness knowledge and to define the problem indicated by the session theme, clarifying what is known about the Charleston earthquake and what knowledge is still needed. These presentations served as a summary of the state-of-knowledge and gave a multidisclipinary perspective.

PROCEDURE 3: The participants responded to the presentations of the speakers and panelists, using questions posed to focus the discussion.

PROCEDURE 4: Discussion groups were convened following the plenary sessions to generate recommendations for future research and mitigation actions.

PROCEDURE 5: A scenario for the hypothetical "Coalinga, South Carolina, earthquake" was presented to introduce a "crisis environment" and a real-time dimension to the plenary discussions.

PROCEDURE 6: Ad hoc discussions on topics not addressed during the plenary and small group discussions added a spontaneous dimension to the workshop.

PELNARY SESSIONS

The overall theme of the workshop was developed in ten plenary sessions. The themes, objectives, speakers, panelists, and discussion questions posed for each session are described below:

SESSION I: THE EARTHQUAKE THREAT

OBJECTIVE: Presentations giving an overview of some of the most important fundamental knowledge about the earthquake threat in the Southeastern United States.

MODERATOR: Leon Beratan

SPEAKERS: Leonardo Seeber, Ted Algermissen, Otto Nuttli, Risa Palm

SESSION II: "COALINGA, SOUTH CAROLINA EARTHQUAKE"

OBJECTIVE: Presentation of a hypothetical scenario to introduce a crisis environment and a real-time dimension to the discussions.

SPEAKER: Charles Thiel

SESSION III: EASTERN SEISMICITY WITH EMPHASIS ON THE CHARLESTON EARTHQUAKE: PROGRESS, PROBLEMS, AND COMPETING HYPOTHESES

OBJECTIVE: Presentations describing the state-of-knowledge concerning the Charleston earthquake, important geological and seismological data, the scientific and technical issues that need resolution, and one or more of the various proposed tectonic models.

DISCUSSION QUESTIONS: Is there yet a preferred or preferable tectonic model for the Charleston earthquake?

What is the role of geological and/or seismological uniqueness in the tectonic models or hypotheses for the Charleston earthquake?

Are the currently available deep reflection profiles conclusive or not?

MODERATOR: Paul Pomeroy

RECORDER: Andrew Murphy

SPEAKERS: Leonardo Seeber, John Behrendt, Gilbert Bollinger, Carl Wentworth, Pradeep Talwani, Nick Ratcliffe

SESSION IV: ROLE OF GEOLOGICAL AND GEOPHYSICAL INVESTIGATIONS IN EVALUATION OF CRITICAL HYPOTHESES

OJBECTIVE: Presentations recommending critical geological and geophysical experiments to resolve questions concerning the Charleston earthquake.

DISCUSSION QUESTIONS: What is the origin of the stress field?

What is the role of deep drilling to identify the causative faults?

How significant is seismic reflection profiling, including COCORP?

Can earthquake source parameters and mechanisms be specified more accurately?

What information can be gained from potential field surveys?

MODERATOR: Steve Brocoum

RECORDER: Tom Schmitt

SPEAKERS:

Mark Zoback	Greg Gohn
Kim Klitgord	Leland Long
John Costain	Roger Stewart
James McWhorter	

SESSION V: ENGINEERING RESEARCH GOALS FOR EARTHQUAKE-RESISTANT DESIGN AND PROBLEMS OF HISTORIC PRESERVATION

OBJECTIVE: Presentations emphasizing earthquake-resistant design of structures and problems of historic preservation, specifying important technical and social issues and recommending solutions.

DISCUSSION QUESTIONS: Are the seismic design provisions of the current editions of the various building codes (e.g., Uniform Building Code, BOCA, etc.) reasonable and adequate for earthquake-resistant design of buildings in the Southeastern United States?

Is the Applied Technology Council's 1978 model building code more appropriate?

What kind of scientific and technical information is needed to improve seismic design?

Is strengthening and retrofitting of existing buildings a viable option?

Should earthquake resistance of single family dwellings be improved?

MODERATOR: William Hakala

RECORDER: Carl Simmons

SPEAKERS: James Nau, Edgar Leyendecker, Larry Kahn, O. Clarke Mann, Roland Sharpe, Fred Rossini

SESSION VI: GOALS CONCERNING EARTHQUAKE HAZARD AWARENESS

OJBECTIVE: Presentations citing important social issues, emphasizing hazard awareness activities and results that can be transferred from other geographic areas to the Southeast.

DISCUSSION QUESTIONS: What is the current level of hazard awareness and concern in the Southeastern United States?

What actions will improve awareness and concern substantially in the next 5-10 years?

MODERATOR: William Anderson

RECORDER: Ugo Morelli

SPEAKERS: Harry Lambright, Joyce Bagwell, John Loss, Steve Kinard, Joanne Nigg

SESSION VII DISASTER PREPAREDNESS

OBJECTIVE: Presentations emphasizing the concept of multiple hazards preparedness noting important societal issues and emphasizing geographic areas that can be transferred to the Southeast.

DISCUSSION QUESTIONS: What is the current state-of-preparedness in the Southeastern United States?

Is it adequate?

What actions will improve the state-of preparedness substantially in the next 5-10 years?

MODERATOR: Richard Sanderson

RECORDER: Robert Scott

SPEAKERS: Charles Lindbergh, Winn Carter, Bill Bivins

SESSION VII: ROLE OF HISTORICAL SEISMICITY VERSUS TECTONICS AS INDICATORS OF SEISMIC HAZARD

OBJECTIVES: Presentations describing the roles of historical seismicity and tectonics as antagonists and/or protagonists to indicate the level of seismic hazard.

DISCUSSION QUESTIONS: What is the role of historical seismicity (presence and absence) as an indicator of seismic hazard?

What is the role of aftershocks in the baseline of Charleston seismicity?

Is recent seismicity the best indicator of seismicity in the near-future?

How important is the role of tectonics in the evaluation of the seismic hazard?

MODERATOR: Bob Jackson

RECORDER: Dave Perkins

SPEAKERS: Leon Reiter, James Dewey, Pradeep Talwani, Patrick Barosh, Jim Devine, Gilbert Bollinger, Robin McGuire

SESSION IX: LARGE INTRAPLATE EARTHQUAKES (M OF 7.0 OR GREATER) AT OTHER LOCATIONS: ANALYSIS AND COMPARISON WITH CHARLESTON

OJBECTIVE: Presentations suggesting what can be learned from study of other large intraplate earthquakes (e.g., New Madrid, La Malbaie, Ottawa-Grand Banks, and Meckering) to resolve unresolved technical issues concerning the 1886 Charleston earthquake.

MODERATOR: Carl Stepp

RECORDER: John Armbruster

SPEAKERS: James Dewey, Otto Nuttli, Peter Basham, Frank McKeown, Gabriel LeBlanc, Kevin Coppersmith

SESSION X: RESEARCH PLANS FOR THE FUTURE: INTEGRATED PLANS OF FEDERAL AGENCIES AND OTHERS WORKING IN THE CHARLESTON REGION

OBJECTIVE: Presentations describing current plans for research and other activities in the Southeastern United States.

SPEAKERS:
Ted Algermissen, U.S. Geological Survey
Andrew Murphy, Nuclear Regulatory Commission
William Anderson and Leonard Johnson, National Science Foundation
Edgar Leyendecker, National Bureau of Standards
Ugo Morelli, Federal Emergency Management Agency
Ellis Krinitzsky, Corps of Engineers
Bill Seay, Tennessee Valley Authority
Ian Wall, Electric Power Research Institute

DISCUSSION GROUPS: FOUR SIMULTANEOUS DISCUSSION GROUPS TO DEFINE CONCENSUS AND TO RECOMMEND THE NEXT STEPS

Discussion Group 1: Results and Role of Current Seismicity--Results of network investigations, depths, and focal mechanism.

Moderator: Pradeep Talwani, University of South Carolina
Recorder: David Amick, Ebasco Services
Stimulator: Susan Rhea, U.S. Geological Survey

Discussion Group 2: Results and Role of Geologic Investigations--Stratigraphy, structure, quaternary studies, paleoliquefaction, and deep drilling.

Moderator: Robert Morris, U.S. Geological Survey
Recorder: Donald Caldwell, Golder Associates
Stimulator: Greg Gohn, U.S. Geological Survey

Discussion Group 3: Results and Role of Geophysical Investigations--Reflection and refraction studies, potential field studies, and stress measurements.

Moderator: Mark Zoback, U.S. Geological Survey
Recorder: Ina Alterman, U.S. Nuclear Regulatory Commission
Stimulator: I.W. Marine, E.I. Dupont Co. (Reflection Studies)
Kim Klitgord, U.S. Geological Survey (Potential Field Studies)

Discussion Group 4: Increasing Hazard Awareness and Preparedness

Moderator: Norman Olsen, South Carolina Geological Survey
Recorder: Phyllis Sobel, U.S. Nuclear Regulatory Commission
Stimulator: Joyce Bagwell, Baptist College at Charleston
O. Clarke Mann, Consulting Engineer

SUMMARY OF RECOMMENDATIONS

On the basis of the plenary sessions and the discussion groups, the participants proposed the following recommendations:

1) The efforts of SCSSC, the South Carolina Geological Survey, and their partners in the South Carolina Office of Emergency Services to increase the awareness, concern, and state-of-preparedness in the Southeast must be continued and strengthened.

2) USGS must continue their efforts to produce a synthesis of the research to date and to devise an integrated research plan for Eastern

seismicity, giving top priority to clarifying and resolving technical issues associated with the dozen or so seismotectonic models.

3) An integrated multidisciplinary research program must be continued by USGS and NRC in order to obtain a complete understanding of the cause of the 1886 Charleston earthquake within the regional tectonic framework.

3) USGS, NRC, and NSF should work closely to formulate strategies, set priorities, and encourage interest in the scientific/engineering community for future research in the Charleston region.

ACKNOWLEDGMENTS

A special note of appreciation is extended to each of the following individuals for the contributions:

1) The Steering Committee of Ted Algermissen (USGS), Leon Beratan (NRC), John Behrendt (USGS), Gilbert Bollinger (Virginia Polytechnic Institute and State University), William Butcher (NSF), Paula Gori (USGS), Walter Hays (USGS), Robert Jackson (NRC), Leonard Johnson (NSF), Edgar Leyendecker (NBS), Bob Morris (USGS), Ugo Morelli (FEMA), Otto Nuttli (St. Louis University), Norman Olson (South Carolina Geological Survey and SCSSC), and Pradeep Talwani (University of South Carolina) planned and organized the workshop.

2) The participants who joined in the plenary sessions and the discussion group were the key to the success of the workshop. Their vigorous and healthy exchange of ideas made the workshop pratical and interesting.

3) Joyce Bagwell, Charles Lindbergh, Norman Olsen, and Pradeep Talwani provided valuable assistance in arranging logistical support, press conferences, and solutions to meet a variety of needs.

4) Carla Kitzmiller, Joyce Costell, Cheryl Miles, Susan Kibler, Diana Darnell, Beth Bufa, Lynne Downer, Wanda Fuller, and Peggy Randalow provided strong and capable administrative support.

EVALUATION OF "THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE AND ITS IMPLICATIONS FOR TODAY"

by

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Evaluations returned by approximately 80 participants in the "Workshop on the 1886 Charleston Earthquake and Its Implications for Today," held in Charleston, South Carolina, May 23-26, 1983, indicate that the workshop was a success by nearly all measures. First we will look at the responses from the entire group. Then we will examine responses provided by specific groups of participants: physical scientists, a group comprised of geologists, geophysists, and seismologists; engineers; federal decisionmakers; social scientists and historians; and, finally, State and local officials.

The attached sample questionnaire, Figure 1, provides a breakdown of responses of those 78 individuals who returned a legible evaluation sheet. The conference had several goals: to define the state of knowledge about geologic, engineering and societal aspects of the 1886 Charleston earthquake in the context of eastern seismicity; to identify the most important scientific, technical, and societal issues arising from the 1886 Charleston earthquake; to assess earthquake-resistant design of buildings and critical facilities, and earthquake hazard reduction preparedness in the Eastern United States; to recommend research and implementation actions to resolve the most important issues; and finally to identify possible resources for future research and action.

Nearly 90% of those who participated in the evaluation agreed that the workshop was useful in defining the state of knowledge, particularly about geologic aspects of the 1886 event. Approximately 70% of those who submitted an evaluation felt that the workshop was successful in identifying and discussing the most important scientific, technical, and societal issues arising from the 1886 event, with regard to earthquake-resistant design of

FIGURE 1
COMBINED RESPONSES*

WORKSHOP ON THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE AND ITS IMPLICATIONS FOR TODAY"
MAY 23-26, 1983

	Yes	No
1. Did you find the conference to be useful for:		
a. defining the state-of-knowledge about geologic, engineering, and societal aspects of the 1886 Charleston earthquake in the context of eastern seismicity?	70	8
b. identifing and discussing the most important scientific, technical, and societal issues arising from the 1886 Charleston earthquake and earthquake-resistant design of buildings and critical facilities, and earthquake hazards reduction preparedness, in the Eastern United States?	54	24
c. recommending research and implementation actions to resolve the most important issues?	33	40
d. Identifing possible resources for future research and implementation actions?	44	26
2. Did the conference benefit you or your organization by:		
a. providing new sources of information and expertise you might want to utilize in the future?	46	26
b. establish better understanding of the problems faced by researchers and decisionmakers?	58	19
3. Did you find the following activities useful:		
a. panel discussions	59	17
b. special report of post earthquake investigation teams	45	20
c. small group discussions	72	3
d. adhoc discussions	63	10
e. notebooks and abstracts	63	2
g. conference proceedings (to be published in about 5 months)	66	0
4. If the clock were turned back and the decision to attend the conference or not were given you again, would you want to attend?	68	8
5. Should other conferences of this type be held in the future?	75	8

*** Totals may vary as not all respondents answered all questions.**

buildings and critical facilities and earthquake hazards reduction preparedness in the Eastern United States. The workshop was judged least successful in recommending future research and implementation actions to address the most important research and mitigation issues. Only one-third of those who took part in the evaluation judged the workshop successful in this area. Over half of the participants, however, did think that the workshop was successful in identifying possible resources for future research and implementation actions. Over half of the participants felt that the workshop provided new sources of information and expertise. And the workshop seemed to be particularly successful in providing a better understanding (to 74% of the respondents) of the problems faced by researchers and decisionmakers.

With regard to the organizational aspects of the conference, 75% of the respondents felt that the panel discussions were useful. Only a little more than half felt that the special report on the post-earthquake investigation team of Coalinga was valuable. However, there was nearly unanimous support for the use of small group discussions. Similarly, ad hoc discussions were rated quite high, as were the notebooks and abstracts compiled before the conference. In general, participants seemed positive in evaluating the workshop; nearly 90% would have attended had they known what to expect beforehand, and 96% felt that a similar workshop should be held in the future.

Very detailed and useful comments were submitted by nearly all of the participants, and a number of valuable suggestions were made. We will look at these by group, beginning first with comments provided by the physical scientists.

PHYSICAL SCIENTISTS

Over half of the evaluations were submitted by physical scientists, since they were the majority in attendance. These scientists overwhelmingly felt the workshop was successful in defining the state of knowledge about the 1886 Charleston earthquake and in identifying the important scientific issues surrounding that event. Nearly all of them favor future similar meetings and were pleased to have attended this one. Although more than half of those submitting evaluations felt that the workshop did not recommend research or actions, this group of participants was the most generally positive about the workshop's accomplishments (see Figure 2).

Suggestions were offered to improve future gatherings. Several noted that plenary sessions contained too many formal presentations, and insufficient time for discussion either among panelists or with the larger group. Several respondents were concerned that the scientific discussions failed to provide the kind of consensus which would have been useful to the engineering and management participants. They urged that future gatherings attempt to present conclusions along with the implications so that social scientists, engineers, and planners might incorporate this information into their programs. Others noted that the concurrent small groups prevented interdisciplinary discussions, and suggested mixing participation in the future. Many felt that future conferences should be kept smaller to encourage more effective exchange of ideas.

ENGINEERS

Although the engineers in attendance rated the workshop favorably in its definition of the state of knowledge about the 1886 event, they were nearly unanimous in their criticism that the workshop was too heavily geared to geologists, geophysists, and seismologists. For those with an interest in addressing earthquake mitigation problems, the workshop did not give sufficient attention to such issues as earthquake-resistant design and other earthquake engineering challenges. However, the engineers were unanimous in their support for further conferences, modified to include more engineering aspects and fewer highly technical plenary sessions (see Figure 3).

FEDERAL DECISIONMAKERS

Among those taking part in the workshop were representatives of several federal agencies--the Federal Emergency Management Agency (FEMA), the Nuclear Regulatory Commission (NRC), the Tennessee Valley Authority (TVA), the Corps of Engineers (COE), and the U.S. Geological Survey (USGS). This group, more than any of the others, expressed frustration with the absence of scientific consensus and conclusions. Although these participants were favorable in

FIGURE 2
PHYSICAL SCIENTISTS

WORKSHOP ON THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE AND ITS IMPLICATIONS FOR TODAY"
MAY 23-26, 1983

		Yes	No
1.	Did you find the conference to be useful for:		
	a. defining the state-of-knowledge about geologic, engineering, and societal aspects of the 1886 Charleston earthquake in the context of eastern seismicity?..................................	39	1
	b. identifing and discussing the most important scientific, technical, and societal issues arising from the 1886 Charleston earthquake and earthquake-resistant design of buildings and critical facilities, and earthquake hazards reduction preparedness, in the Eastern United States?	29	12
	c. recommending research and implementation actions to resolve the most important issues?..	18	21
	d. Identifing possible resources for future research and implementation actions?..	21	14
2.	Did the conference benefit you or your organization by:		
	a. providing new sources of information and expertise you might want to utilize in the future?................................	24	14
	b. establish better understanding of the problems faced by researchers and decisionmakers?................................	30	10
3.	Did you find the following activities useful:		
	a. panel discussions..	33	8
	b. special report of post earthquake investigation teams.............	28	11
	c. small group discussions..	39	0
	d. adhoc discussions..	34	8
	e. notebooks and abstracts..	32	2
	g. conference proceedings (to be published in about 5 months)........	32	0
4.	If the clock were turned back and the decision to attend the conference or not were given you again, would you want to attend?.....	39	2
5.	Should other conferences of this type be held in the future?..........	43	4

FIGURE 3
ENGINEERS

WORKSHOP ON THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE AND ITS IMPLICATIONS FOR TODAY"
MAY 23-26, 1983

	Yes	No
1. Did you find the conference to be useful for:		
a. defining the state-of-knowledge about geologic, engineering, and societal aspects of the 1886 Charleston earthquake in the context of eastern seismicity?	10	2
b. identifing and discussing the most important scientific, technical, and societal issues arising from the 1886 Charleston earthquake and earthquake-resistant design of buildings and critical facilities, and earthquake hazards reduction preparedness, in the Eastern United States?	8	5
c. recommending research and implementation actions to resolve the most important issues?	5	6
d. Identifing possible resources for future research and implementation actions?	8	4
2. Did the conference benefit you or your organization by:		
a. providing new sources of information and expertise you might want to utilize in the future?	11	0
b. establish better understanding of the problems faced by researchers and decisionmakers?	10	1
3. Did you find the following activities useful:		
a. panel discussions	10	1
b. special report of post earthquake investigation teams	5	3
c. small group discussions	11	1
d. adhoc discussions	10	0
e. notebooks and abstracts	11	0
g. conference proceedings (to be published in about 5 months)	12	0
4. If the clock were turned back and the decision to attend the conference or not were given you again, would you want to attend?	10	0
5. Should other conferences of this type be held in the future?	12	0

their evaluation of the achievements of the workshop in defining the state of knowledge and identifying important scientific, technological, and societal issues, they felt the workshop failed to provide new sources of information. In their opinion, it especially failed to recommend new research, specifically actions that could be taken to improve earthquake hazard reduction (see Figure 4). Many of these participants thought the long plenary sessions were far too technical, and should have been treated as concurrent sessions aimed specifically at the technical experts in the group rather than at the entire audience. Several of the federal representatives suggested that if future workshops were held, they should be smaller and care should be taken in designing plenary sessions to reflect the concerns of the entire group. Many recommendations were made for greater opportunity for both formal and informal discussion.

SOCIAL SCIENTISTS AND HISTORIANS

Proportionately the most negative reactions to the workshop content and format were registered by the social scientists who participated. Many indicated that the workshop seemed successful in defining the state of knowledge about geologic aspects of the 1886 earthquake, but failed to define the state of knowledge about engineering and, certainly, the societal aspects of this event. Similarly, these participants felt that although the workshop identified important scientific and technical aspects of the 1886 quake, it did little to illuminate societal issues.

Nearly half of the participants would not have attended the conference had they known what to expect, and nearly all of them suggested that should future conferences be held, they should be modified significantly (see Figure 5).

Comments from this group were numerous. Future workshops should not try to address such a broad range of participants with highly technical topics. Technical sessions might better have been held as concurrent sessions rather than as plenary sessions. The plenary sessions were very large and had many technical presentations that prevented discussion and questions from the other groups in attendance. When participants were divided into smaller groups and segregated by discipline--engineers, social scientists, and physical scientists each going to separate sessions--the exchange of ideas was further hindered.

FIGURE 4
FEDERAL DECISIONMAKERS*

WORKSHOP ON THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE AND ITS IMPLICATIONS FOR TODAY"
MAY 23-26, 1983

	Yes	No
1. Did you find the conference to be useful for:		
a. defining the state-of-knowledge about geologic, engineering, and societal aspects of the 1886 Charleston earthquake in the context of eastern seismicity?	12	2
b. identifing and discussing the most important scientific, technical, and societal issues arising from the 1886 Charleston earthquake and earthquake-resistant design of buildings and critical facilities, and earthquake hazards reduction preparedness, in the Eastern United States?	9	4
c. recommending research and implementation actions to resolve the most important issues?	4	9
d. Identifing possible resources for future research and implementation actions?	7	6
2. Did the conference benefit you or your organization by:		
a. providing new sources of information and expertise you might want to utilize in the future?	5	8
b. establish better understanding of the problems faced by researchers and decisionmakers?	11	3
3. Did you find the following activities useful:		
a. panel discussions	9	5
b. special report of post earthquake investigation teams	7	5
c. small group discussions	14	0
d. adhoc discussions	12	2
e. notebooks and abstracts	11	0
g. conference proceedings (to be published in about 5 months)	13	0
4. If the clock were turned back and the decision to attend the conference or not were given you again, would you want to attend?	11	2
5. Should other conferences of this type be held in the future?	12	2

*Includes NRC, FEMA, EPRI, TVA, and Corps of Engineers representatives.

FIGURE 5
SOCIAL SCIENTISTS & HISTORIANS

WORKSHOP ON THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE AND ITS IMPLICATIONS FOR TODAY"
MAY 23-26, 1983

	Yes	No
1. Did you find the conference to be useful for:		
a. defining the state-of-knowledge about geologic, engineering, and societal aspects of the 1886 Charleston earthquake in the context of eastern seismicity?	3	3
b. identifing and discussing the most important scientific, technical, and societal issues arising from the 1886 Charleston earthquake and earthquake-resistant design of buildings and critical facilities, and earthquake hazards reduction preparedness, in the Eastern United States?	3	3
c. recommending research and implementation actions to resolve the most important issues?	2	3
d. Identifing possible resources for future research and implementation actions?	3	2
2. Did the conference benefit you or your organization by:		
a. providing new sources of information and expertise you might want to utilize in the future?	2	3
b. establish better understanding of the problems faced by researchers and decisionmakers?	2	5
3. Did you find the following activities useful:		
a. panel discussions	2	3
b. special report of post earthquake investigation teams	1	1
c. small group discussions	5	1
d. adhoc discussions	4	0
e. notebooks and abstracts	4	0
g. conference proceedings (to be published in about 5 months)	5	0
4. If the clock were turned back and the decision to attend the conference or not were given you again, would you want to attend?	3	2
5. Should other conferences of this type be held in the future?	3	2

The social scientists urged that future workshops be designed to provide greater opportunities to address specific programs of hazard mitigation. Several social scientists made the observation that although both the plenary and concurrent engineering and geoscience sessions were filled with highly trained participants, the social science sessions dealing with awareness contained only two or three actual research scientists; the others came primarily from the management area. This particular mix hindered theoretical discussion in the awareness sessions. The suggestion was made that a larger number of social scientists be involved in future meetings in order to build upon existing research, rather than to simply reiterate well-understood theoretical concepts regarding awareness and mitigation activities. Furthermore, because the scientists and engineers were in other sessions, it was difficult for productive planning to go forward in their absence. Several of the social scientists expressed frustration at the lack of opportunity for discussion about advancement in conceptual research considerations.

STATE AND LOCAL OFFICIALS

The few State and local officials were almost uniformly positive in their evaluations of the workshop. This category included one State planner, a State geologist, a State emergency services official, and two local public works officials. They urged that more emergency services personnel be included in future workshops, and that opportunities for discussion of improving public awareness be expanded (see Figure 6).

CONCLUSIONS

The majority of participants in the workshop judged it to be successful in defining the state of knowledge regarding the 1886 Charleston earthquake, and in identifying and discussing important related scientific and technological issues. With its highly technical, formal plenary presentations, the workshop provided valuable information to members of the geoscience community. It was somewhat less successful in identifying implications for planning and mitigation actions. Care should be taken in planning future meetings to define the central purpose and to keep that in mind in shaping the participant group. Mixing highly technical matter with policy and management concerns may result in an unwieldy program.

FIGURE 6
STATE & LOCAL OFFICIALS

WORKSHOP ON THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE AND ITS IMPLICATIONS FOR TODAY"
MAY 23-26, 1983

	Yes	No
1. Did you find the conference to be useful for:		
a. defining the state-of-knowledge about geologic, engineering, and societal aspects of the 1886 Charleston earthquake in the context of eastern seismicity?	6	0
b. identifing and discussing the most important scientific, technical, and societal issues arising from the 1886 Charleston earthquake and earthquake-resistant design of buildings and critical facilities, and earthquake hazards reduction preparedness, in the Eastern United States?	5	0
c. recommending research and implementation actions to resolve the most important issues?	4	1
d. Identifing possible resources for future research and implementation actions?	5	0
2. Did the conference benefit you or your organization by:		
a. providing new sources of information and expertise you might want to utilize in the future?	4	1
b. establish better understanding of the problems faced by researchers and decisionmakers?	5	0
3. Did you find the following activities useful:		
a. panel discussions	5	0
b. special report of post earthquake investigation teams	4	0
c. small group discussions	3	1
d. adhoc discussions	3	0
e. notebooks and abstracts	5	0
g. conference proceedings (to be published in about 5 months)	4	0
4. If the clock were turned back and the decision to attend the conference or not were given you again, would you want to attend?	5	0
5. Should other conferences of this type be held in the future?	5	0

A number of recommendations follow for future workshops:

1) Highly technical sessions devoted to one group of participants are best handled in concurrent rather than in plenary sessions.

2) Plenary sessions should provide adequate opportunities for questions and discussion from the larger group.

3) Efforts should be made to increase the role of small group discussions; small groups encourage greater interaction and exchange of ideas than do plenary sessions.

4) Broad interdisciplinary participation in small groups should be encouraged, and care taken that concurrent sessions do not compete for the same audience.

SUMMARY OF DISCUSSION GROUP 1

RESULTS AND ROLE OF CURRENT SEISMICITY IN UNDERSTANDING THE 1886 CHARLESTON, SOUTH CAROLINA EARTHQUAKE

by

Moderator: Pradeep Talwani, University of South Carolina

Recorder: David C. Amick, Ebasco Services Incorporated

Stimulator: Susan Rhea, U.S. Geological Survey

INTRODUCTION

Discussion Group 1 examined results of network investigations, depths, and focal mechanisms of earthquakes in the region. The discussion group stimulator, Susan Rhea, opened the session with a discussion of the epicentral and hypocentral distribution as well as focal plane solutions published by several investigators who have evaluated the instrumental data available for the Charleston area.

The moderator then charged the group with 1) assessing the results of the previous seismic network investigations in the Charleston area and 2) defining the role of the seismic network in the future. Discussion centered primarily around the quality of the instrumental seismic data collected over the last 10 years and its limitation in determining the seismogenic source of the 1886 Charleston earthquake.

The discussion indicated that there is a wide range of opinion of the quality of existing instrumental data and its applicability to the identification of the source of the 1886 event. Nonetheless, the discussion group did reach a consensus on several issues regarding the interpretation of results obtained from recent instrumental data. Collectively, the group made several recommendations regarding the role of seismic networks in future investigations.

GROUP CONSENSUS

The Webster's dictionary defines consensus as: "a general agreement or the judgement arrived at by most of those concerned". Therefore, the existence of a minority opinion is expected and is acknowledged. The following consensus statements are given as phrased and approved by the discussion group. Following each statement a brief discussion explains its possible implications on the question of evaluating seismic risk in the Eastern United States. The contents of this report were presented by the recorder to the entire workshop on May 26, 1983, as part of the discussion groups summary reports.

Consensus No.1

The current earthquakes that occur at Charleston are not aftershocks of the 1886 event. This suggests that there is a local structure at Charleston that is the source of the continued seismic activity.

Implicaticns:

This is an important observation and one with several possible implications. First, several authors had suggested that because the instrumentally recorded seismicity at Charleston may be aftershocks of the 1886 event, their spacial distribution and source mechanism may reflect perturbations in the local stress field brought about by deformation associated with the 1886 event. Therefore, the hypocenters and focal mechanisms derived from these events may not necessarily identify the seismogenic source or causative mechanism of the 1886 event. Now, however, one could infer, based on the group's consensus, that since the instrumentally documented seismicity is not aftershocks of the 1886 event and since it is located in close proximity to the mezoseismal area of the 1886 event, its spacial distribution and focal mechanisms should aid in the identification of the causative structure and source mechanism of the 1886 event. Another implication that could be drawn is that since the instrumentally documented seismicity is not aftershock activity of the 1886 event, then it identifies a seismogenic source which exhibits a background level of seismicity in excess of the normal regional seismic flux. Taking this a step further it could be suggested that areas that may represent potential sources similar to the Charleston source should also be associated with similar levels of background seismicity.

Consensus No.2

The hypocentral distribution of the instrumentally located seismicity at Charleston defines nearly vertical zones of activity. It does not support seismic activity along a horizontal or subhorizontal plane. The decollement structure suggested by some authors to be the source of 1886 event is not a preferred model. However, the possibility exists that aseismic movement along a decollement structure at depth could be a driving mechanism for the observed activity along steeply dipping planes shallower in the crust.

Implications:

There are several implications that can be drawn from these observations. First, and foremost, the consensus suggests that deterministic seismic risk studies in the Eastern United States should not model a subhorizontal decollement structure as a seismogenic source capable of generating great thrust or backsliding events. Second, although the group acknowledged that activity appears to be taking place along nearly vertical planes, the qualification that this movement may be in response to aseismic deformation along a subhorizontal structure suggests that suitably oriented vertical zones of weakness in the crust of the Eastern United States should possibly be modeled as capable structures in deterministic seismic risk studies.

Consensus No.3

The causative fault of the 1886 event has not been unequivocably identified. This statement is based on the observation that the distribution of hypocenters fail to unequivocably define a clear seismogenic structure. Comments from the group indicate that although composite focal mechanisms solutions have been published, and when interpreted together with hypocentral data tend to identify seismogenic structures, the focal plane solutions in and of themselves are nonunique. The ambiguity in the focal plane data is due to 1) the questioned validity of the clustering or grouping of events used in the composite solutions, 2) the observation that the impact of heterogeneities in the lateral velocity may not have been adequately taken into account during the modeling of first motion data.

Implication:

In the absence of reliable focal plane data which can be used to determine the orientation of the maximum principle stress in the region, a critical evaluation of the relative merits of the various models proposed to explain the causative mechanism of the 1886 event is extremely difficult.

RECOMMENDATIONS

The group suggested that the Charleston seismic network be upgraded from the present narrow band analog single component system to a broad band digital system incorporating three component borehole sites. The present network was designed under the assumption that the rate and level of seismicity at Charleston would be significantly greater than that recorded over the past 10 years. A broad band digital network would have a significantly lower detection threshold thus increasing the data set available for study, making it possible to determine single-event focal plane solutions with input not only from first motion data but also data on S wave polarity and Sv/P ratios.

It was also suggested that the network be calibrated to provide input to attenuation studies, which will be needed if a realistic probabilistic evaluation is to be carried out. Finally, the group suggested that the goals of the network be set to: 1) delineate the source of the present seismicity and 2) determine focal plane solutions in order to define the orientation of principal stress. These advances would provide a means to evaluate the various models proposed as a source of Eastern United States seismicity.

SUMMARY AND RECOMMENDATIONS OF DISCUSSION GROUP 2: RESULTS AND ROLE OF GEOLOGIC INVESTIGATIONS

by

Moderator: Robert H. Morris, U.S. Geological Survey
Recorder: Donald M. Caldwell, Golder Associates
Stimulator: Gregory S. Gohn, U.S. Geological Survey

INTRODUCTION

About fifty persons representing academia, geologic research institutes, consulting firms, and State and Federal government agencies participated in discussion Group 2. The group concluded that the roles of geologists in earthquake studies include: providing basic geotechnical data for direct use by engineers in the design and construction of major facilities; providing geologic information to seismologists who, in turn, apply these data for interpreting the location, frequency, and size of past and future earthquakes; and utilizing geologic data, in conjunction with geophysical data, to formulate and test seismotectonic models.

ROLE OF GEOLOGIC INVESTIGATIONS

In order for geologists to fulfill these roles, the group noted the necessity of having an adequate geologic data base that includes the following:

1) Geologic maps. Regional maps should be at 1:250,000 or 1:125,000 scale; local or site-specific maps should be at 1:24,000 scale; all maps should be compiled on appropriate modern topographic bases.

2) An understanding of the regional tectonic history and structural setting.

3) A comprehensive regional and local stratigraphic framework.

4) Hydrologic surveys of the subsurface water regime.

PRESENT STATE OF KNOWLEDGE

To evaluate our present state of knowledge of the Charleston, S.C., region, the existing geologic data were inventoried. These include:

1) Existing geologic maps at 1:250,000 scale showing the distribution of geologic units as defined in several hundred shallow (30- to 100-foot deep) auger holes.

2) Geophysical surveys of aeromagnetic and gravity data on a regional scale, refraction profiles, and reflection profiles ranging from deep (COCORP) to intermediate and shallow penetration.

3) Seismologic data from the historic record and a catalog of modern seismicity based upon the regional Southeastern United States seismic network and the more locally deployed Charleston, S.C., network, which has been functioning since 1973.

4) Regional reconnaissance mapping of the Atlantic Coastal Plain southward from North Carolina; regional subsurface stratigraphic data obtained from drill holes at Britton's Neck, St. George, and Clubhouse Crossroads; numerous drill holes in the Savannah River Plant area; various municipal water wells; and various geologic reports for the Savannah River Plant and the Vogtle Nuclear power plant site in adjacent Georgia.

5) Additional geologic data such as geochemical, petrologic, and paleontologic analyses of subsurface units.

6) Regional hydrocarbon-resource studies of the Continental Shelf that contain marine seismic-reflection profiles and interpretive reports and stratigraphic data for the few offshore stratigraphic test holes.

7) A growing data bank resulting from various doctoral theses and other academic reports.

The group discussed the adequacy of the existing data and noted that the new USGS geologic maps (at several scales) are excellent in their depiction of surficial and shallow-subsurface geology. However, a series of deeper drill holes would be needed to extend our knowledge downward in an effort to delineate, through integration with geophysical data, the configuration of the deeper subsurface geology.

There was a recognition of a number of potentially limiting factors regarding detection and mapping of Cenozoic faults in the Atlantic Coastal Plain. These are:

1) To date, no active surface fault rupture has been recognized in the Eastern United States.

2) Anticipated late Cenozoic fault slips of one meter are difficult to detect in coastal areas due to erosion of surficial deposits and modification or masking of surficial features by vegetation and cultural development.

3) The cut-and-fill history of Cenozoic depositional units could easily mask young faults.

4) The interpolated fault-movement rate of one meter per million years may not be valid because the rate is derived from net vertical offset and exposures of opportunity which may not represent the average or extreme value of slip.

5) The results of seismic reflection surveys need to be refined and extrapolated to shallow depths. Any structures recognized in the seismic profiles should be particular targets of opportunity for detailed subsurface investigations or trenching where feasible. Some newly developed geophysical techniques such as ground-penetrating radar and electrical resistivity may be useful in delineating near-surface structures. Emphasis should be placed on determining the youngest recognizable fault offset, recurrence rates, and nature of offset. The group recognized that there is a growing body of

evidence for Cenozoic faulting in the southeastern Coastal Plain. The Belair, Strafford, Brooks, and similar structures are characterized by reverse movement, moderate displacement, and offset rates of about 1 meter per million years. These faults trend NNE and many appear to be related to older faults.

The group recognized that there may or may not be a direct relationship of shallow faults to the deeper source structures. If the interpretation of Dr. Otto Nuttli is correct that the probable epicenter of the 1886 Charleston event was about 20 km deep, there may not necessarily be a direct relation to the present shallower seismicity or to shallow structures such as the Cooke or Gants faults. Futhermore, it was pointed out (by Dave Prowell, U.S. Geological Survey) that Cenozoic faults have been found where: 1) Paleozoic faults are present, 2) Mesozoic faults are present, and 3) no earlier faults are recognized. Consequently, there may not be any "preferred" structures for reactivation in terms of age or type of displacement.

FUTURE WORK

There was an overwhelming consensus that a synthesis of presently available data should be the primary objective of the moment. The synthesis should incorporate an evaluation of the various proposed tectonic models and recommendations as to how such models could be tested and verified.

It was recommended (by Nick Ratcliffe, U.S. Geological Survey) that structural investigations should be focused on areas where we have: 1) good instrumental data on earthquakes, 2) a means of tracing structure to the surface (i.e. seismic reflection records), and 3) access to rocks similar to those at hypocentral depths. This recommendation would lead to concentrating efforts in areas like central Virginia and central New Hampshire. The expectation was also expressed that these investigations will result in recognition of multiple causes and faults as candidates for seismic sources.

Now that a good basic geologic map is available, an engineering geologic map should be compiled that would include:

1) The distribution of 1886 sand blows.

2) The distribution of soil types and their potential for liquefaction or failure.

3) The geotechnical properties of surficial materials.

4) A re-examination and interpretation of the effects of the 1886 earthquake as recorded by Dutton in light of the foregoing engineering map.

Stress measurements should be continued with the objective of better defining stress provinces. Improved knowledge of the modern stress regime would help to delineate those structures with the highest potential for movement under that regime.

Addtional studies which might be investigated include:

1) Geodetic surveys to assess recent deformation.

2) Geomorphic studies aimed at identifying tectonic effects through analysis of the distribution of Quaternary sediments, drainage patterns, and changes in sea level.

3) Hydrologic studies that incorporate the body of data available in State and USGS Water Resources Division files. These data would be relevant to studies of regional aquifers, the piezometric surface, and chemical anomalies related to structure.

4) Studies of fault properties, specifically those properties which might control slip under varying conditions of stress.

5) Studies of paleoliquefaction features. Knowledge of the ages of seismically induced, pre-1886 sand blows and related phenomena would be important in determining the recurrence interval of major earthquakes in the Charleston region.

The group emphasized the necessity for integrated multidisciplinary programs to perform the research. Hence, seismic-reflection, seismic-refraction, gravity, and magnetic surveys (including paleomagnetics) and earthquake-monitoring studies should also be conducted.

Questions which are important but not specifically addressed by the recommendations of the group are:

1) What are the individual roles (if any) of high-angle reverse faults, strike-slip faults, and low-angle faults in producing large earthquakes.

2) What investigations can be performed to learn about processes acting at hypocentral depths?

3) How can we explain why some faults have apparently moved over long periods of time and others (even some which are similarly oriented) have not?

SUMMARY OF AND RECOMMENDATIONS OF DISCUSSION GROUP 3: RESULTS AND ROLE OF GEOPHYSICAL INVESTIGATIONS; REFLECTION AND REFRACTION STUDIES, POTENTIAL FIELD STUDIES, AND STRESS MEASUREMENTS

Moderator: Mark Zoback, U.S. Geological Survey
Recorder: Ina Alterman, U.S. Nuclear Regulatory Commission
Stimulator: I. W. Marine, E.I. Dupont Company

INTRODUCTION

Recent seismic reflection profiles in the Southeastern United States and in the Charleston area have been quite successful. The major decollement beneath the Appalachians discovered by seismic reflection profiling has dramatically changed interpretation of the geologic history of the Eastern United States. The decollement was developed during continental collision after closure of the proto-Atlantic in Paleozoic time. Although several investigators have tried to establish an association between the Charleston earthquake and this decollement, several lines of evidence suggest that the decollement is not currently active. The Charleston reflection profiling has uncovered several northeast trending faults in the area and defined the location of Triassic Basins. There is no clear association, however, between the faults and either the 1886 Charleston earthquake or the on-going seismicity in the area. One major problem has been the inability to shoot lines in optimal locations because rivers and swamps make critical areas inaccessible. Two types of seismic reflection work in the Charleston area is recommended for the future - high resolution profiles to search for offsets in shallow, young sediments, and deep crustal profiles to define large-scale structures.

Also recommended for defining large-scale structures in the Charleston area was extensive deep crustal seismic refraction studies. An important additional benefit of such work is that improved knowledge of crustal structure and seismic velocities will contribute to much more precise earthquake epicenter and focal mechanism determinations.

structures. Unfortunately, one feature that has been "pointed at" by such data, oceanic fracture zones, have been badly misinterpreted by some investigators with respect to their possible relationship to current seismicity near Charleston and other areas in the East. Oceanic fracture zones are not large-scale active faults. Instead, the fracture zones are active only for brief periods when they act as transform faults along offset segments of the oceanic ridge system. The fracture zones extending across the western Atlantic seafloor are simply markers of past activity which represent growth of the seafloor. Thus, hypotheses that suggest that such features are currently active and responsible for contemporary seismicity are probably incorrect.

RECOMMENDATIONS

It was recommended that more information be gained about the in-situ stress field in the Charleston area and throughout the Eastern United States. Understanding the origin of the forces responsible for eastern earthquakes is as important as knowing about the faults along which the earthquakes occur. In order to assess seismic hazard along the eastern seaboard it is crucial to answer several questions about the in-situ stress field:

1) Is the stress field in the Eastern United States similar to that in the Central United States?

2) Do structures similar to that found in the New Madrid area exist and are they likely to be activated in the current stress field?

3) Are there possibly unique aspects of the stress field which control the location of large intraplate earthquakes?

4) Does the same stress field act throughout the Eastern United States? If so, does it mean that Charleston type earthquakes might occur elsewhere along the eastern seaboard?

In order to answer these provocative questions, more and better data are needed throughout the region on the in-situ stress field.

SUMMARY AND RECOMMEDNATIONS OF DISCUSSION GROUP 4: INCREASING HARARD AWARENESS AND PREPAREDNESS

Moderator: Norman K. Olson, South Carolina Geological Survey
Recorder: Phyllis Sobel, U.S. Nuclear Regulatory Commission
Stimulator: Joyce Bagwell, Baptist College at Charleston

INTRODUCTION

The objectives of Discussion Group 4 were: 1) To develop strategies for increasing the awareness concern part of our topic more or less equally with the preparedness aspect, and 2) to produce a consensus, by the end of the two-hour session, on the significant points and relevant responses to each.

Each stimulator presented a brief preamble to initiate discussion by the audience of approximately 30. The discussion was aided considerably by the leaders and panelists from Session III, Goals Concerning Earthquake Hazard Awareness and Preparedness. Professor Bagwell narrated some of her experiences in the Charleston-Summerville area and surrounding counties in her capacity as operator of the seismograph station at the Baptist College at Charleston. She then distributed a sheet of facts and questions (Appendix 1) to encourage discussion. Mr. Mann stated that awareness starts with knowledge. He admonished the group, "You have a duty to society, not just an opportunity." He then posed two questions as follows:

1) How much do you know about the human effects from earthquake damage.
2) Are you qualified to carry the message to your community?

When asked to raise their hands for question number 2 seven indicated "yes"; 20, "no" and four, "don't know."

Mr. Mann later presented a combination scenario and oral quiz, (Appendix 2), the latter taken by the group near the end of the session.

Mr. Jones made a brief statement on earthquake preparedness. He distributed an outline (Appendix 3) describing the FY 84 program and objectives on the subject by the Federal Emergency Management Administration (FEMA).

AWARENESS

The results of the Charleston earthquake scenario quiz surprised many members of Discussion Group 4. If the 1886 Charleston earthquake were to recur, 80 percent of the commercial buildings and 80 percent of the schools in the epicentral area would be damaged beyond the point of safe occupancy. Frame residences (not on stilts), 15 percent damaged; (on stilts), up to 85 percent damaged. Masonry residences, 70 percent damaged. Estimated number of people killed: 500-1,000. Among those deaths approximately 70 percent would be students. Most of the group's estimates were significantly below the figures based upon recently observed earthquake damage elsewhere. These rough estimates for the purpose of the scenario, were based upon recorded effects of two damaging earthquakes: Eastern Tennessee (November 1973) and Coalinga, California, (April 1983). Mr. Mann pointed out that the purpose of the quiz was to demonstrate that, although we all have a responsibility to disseminate our knowledge of earthquake risks, we should be prepared to defend our damage estimates before speaking to the public or local officials.

The group agreed that, in speaking engagements, we should set specific goals geared to the audience. Examples:

1) Advise families on setting aside water supplies and canned food;

2) Suggest to school officials or the PTA the advantages of having earthquake drills; and

3) Emphasize to builders the need to design and construct schools, hospitals, and other critical facilities to withstand damaging earthquakes.

Some studies suggest that ethnic background and race are factors in awareness and preparedness. Preparedness strategies should take into account the diversity of communities in the area. Furthermore, the approach in speaking to business and professional groups, for example, would differ from that of addressing government leaders or school groups. Packaging the information disseminated on hazard awareness and preparedness into various blocks or modules to fit the audience is critical.

The news media are often influenced by recent local earthquakes or by meetings such as this one. Government agencies and professional societies are also able to make the public aware of earthquake risks. The public, in turn, influences officials who may or may not move toward preparedness. Based upon the discussion group's experience, there are varying levels of earthquake awareness among the public, but local officials will not implement preparedness techniques if they perceive the probability of a damaging earthquake to be low. Even where the building code contains provisions for seismic-resistant design, if the officials believe the seismic hazard is low, builders will not comply with the seismic design part of the code. In Charleston, for example, the newly built Marriott Hotel and the reconstructed Veterans Administration Hospital are the only buildings designed to withstand a damaging earthquake.

PREPAREDNESS

The discussion group was divided over whether or not earthquake hazards should be integrated with other hazard programs. Some members felt that this could be recommended in areas where the probability of a damaging earthquake is low, and that the public should be able to deal with a variety of hazards. Others felt that different hazards require different strategies. Earthquakes are especially unique because there is no warning and they can affect multistate areas.

The group did agree that preparations for a large earthquake in the Charleston area are not being addressed adequately. The best solution is to improve structures (buildings, bridges, overpasses, power substations, and related construction) to withstand damaging earthquakes. Meanwhile, the public should be prepared to react to a damaging earthquake when it is happening because there will likely be no warning.

The emergency preparedness staff in the three-county area of Charleston has presented lectures to the schools, but no earthquake drills. Other talks have been presented to area civic groups and hospitals. There is a general 7isaster plan which includes earthquakes. The implementation of a seismic-resistant design in the building code should come from the State level, and new design or planned retrofitting of existing buildings should place high priority on critical facilities such as schools, fire stations, hospitals and power stations. In the Charleston area the emergency preparedness people are trying to get the schools to purchase radios so they can receive disaster information quickly.

One member suggested that private industry join with government in earthquake hazard preparedness methods. One important example is that businesses are becoming concerned about the effects of ground motion on their computers.

CONCLUSION

Thorough indoctrination of task force members in the many aspects of both awareness of and preparation for earthquake hazards is vital prior to public appearances of the team. Be sure the presentation is relevant to the group. Know your audience. Economic, social, educational, and occupational backgrounds vary widely. The best solution for overall preparedness is to implement seismic-resistant design into the building codes. Retrofitting the various critical structures (hospitals, schools, fire stations, others) to meet seismic-resistant standards may be costly but it could save lives and future financial loss.

A multihazard approach should be emphasized, particularly in areas where damaging earthquakes are rare. Earthquake hazard awareness and preparedness should be included as topics along with tornadoes, floods, hurricanes and other natural disasters.

Appendix 1

MISCELLANEOUS EARTHQUAKE HAZARD FACTS AND QUESTIONS

By Joyce B. Bagwell

Do You Know...

1) In South Carolina approximately 63 earthquakes have occurred in the past 10 years. More than half of these occurred in the Middleton Gardens area.

2) Interviews with public officials and representatives of the educational community and civic organizations indicate some awareness but no preparedness.

3) What is the chain of command concerning community lifeline facilities?

4) In the disaster plan, what is written specifically for earthquakes?

5) What material is available to the general public, homeowners and business community to know what to do in case of a major earthquake?

6) On the State level, how would officials and citizens react in the case of a major earthquake?

7) The Summerville-Charleston community has responded to intensity surveys of the earthquakes between 1977 and 1983. There is a state of awareness and questions have been asked about preparedness.

8) The Veterans Administration Hospital has been reconstructed to withstand a damaging earthquake. This project is near completion.

9) Banks have withheld funds until the recently built Marriott Hotel has been made earthquake safe.

10) One earthquake drill has been held at the Coastal Center, in Ladson, South Carolina.

Appendix 2

"SCENARIO QUIZ ON LOSSES SUSTAINED FROM AN 1886 CHARLESTON EARTHQUAKE" OCCURRING IN MAY 1983

By O. Clarke Mann

Assumptions:

1) The 1886 Charleston earthquake has recurred at 3:00 p.m., May 25, 1983.

2) Among the residences in the area, 70 percent are frame, 30 percent are masonry.

3) None of the commercial structures are earthquake-resistant.

4) None of the school structures are earthquake-resistant.

5) Population of Charleston is 100,000 (for ease of calculations; actually, three-county metropolitan area population estimated at 400,000).

Questions:

1) What percentage of the following structures would be damaged beyond the limits of safety?

    a) Frame residences
    b) Masonry residences
    c) Commercial buildings
    d) Schools

2) How many people would die as a direct result of the earthquake?

3) Of the total number of deaths, how many would be students?

Appendix 3

EARTHQUAKE PREPAREDNESS

By James R. Jones

Description of Program: Thirty-nine of the 50 States have major or moderate seismic risk. Efforts of the Earthquake Preparedness Program of the Federal Emergency Management Administration (FEMA) include:

1) Providing grants to States for vulnerability analyses and contingency plans,

2) Providing technical assistance,

3) Developing improved seismic building practices and standards, and

4) Developing preparedness and mitigation guidelines on earthquakes for incorporation into an integrated emergency management process.

Program Budget Request: $2.1 million.

FY 1984 Objectives: Funds will be used to support not only State preparedness planning efforts but also those initiatives which have a broad national applicability to further improved seismic building policies. FEMA will continue to develop, publish and disseminate materials on life safety and earthquake preparedness and mitigation measures for users in the public and private sectors. In FY 84, States will be requested to identify opportunities to apply the methodologies for performing vulnerability analyses and developing contingency plans to the broader spectrum of hazards as part of an integrated emergency management system. Assistance to the States in FY 84 will provide for the following:

1) Conduct vulnerability analyses, including specific vulnerabilities of critical/special facilities in local jurisdictions in Puerto Rico, San Diego and the Central United States.

2) Continue and enhance contingency planning in the Central United States and San Francisco Bay area.

3) Develop and implement nonstructural mitigation preparedness programs for local jurisdiction in the Central United States, Alaska, Hawaii, San Franscisco, Puget Sound, Boston and Salt Lake City areas.

4) Test and exercise contingency plans in Puget Sound, Boston, Salt Lake City and Central United States.

5) Identify post-earthquake recovery/reconstruction mitigation opportunities in Alaska and Hawaii.

6) Establish local planning councils in Charleston, South Carolina, and upper New York State areas.

7) Initiate cooperative planning projects with the private sector in the Central United States, San Francisco, Salt Lake City and San Diego study areas.

Other efforts in public education, including the adaptation and transfer of the Southern California Earthquake Preparedness Project prototype products and processes, will aid all the States in earthquake planning and preparedness. (From outline program and budget plan from FEMA.)

1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE REVISITED

by

Otto W. Nuttli
Saint Louis University
St. Louis, Missouri 63103

INTRODUCTION

The 1886 Charleston, South Carolina, earthquake can be considered in various ways. The first way is a scientific approach, in which the basic facts are presented in the form of numerical information. Another way is to describe, in a journalistic manner, the effects of the earthquake. A third way is to invision consequences of a future earthquake of similar size. This paper will utilize all three approaches, at least in summary fashion.

QUANTITATIVE INFORMATION

Coffman et al (1982) described the mainshock of the 1886 event as consisting of two earthquakes which occurred at 21^h51^m and 21^h59^m (EST) on Tuesday, August 31, 1886. Bollinger (1977) reinterpreted the intensity data and assigned an MM intensity value of X to an elliptical area of about 1300 km^2. The center of the area, which can be considered as an approximation of the epicentral location, is at the town of Middleton Place, at latitude 32.90° N and longitude 80.14° W, approximately 25 km northwest of Charleston. Because the earthquake just preceded the installation of seismographs in the United States, its magnitude only can be estimated or inferred from the intensity data. Nuttli et al (1979) presented several different methods for estimating the body-wave magnitude (m_b) from the intensity data. They obtained m_b values between 6.6 and 6.9, with a preference for the value of 6.6, for the 1886 earthquake. Nuttli (1983) found that for mid-plate earthquakes an m_b of 6.6 corresponds to a surface-wave magnitude (M_S) of 7.5. For large earthquakes, M_S often is called the Richter magnitude. From scaling relations for mid-plate earthquakes, Nuttli (1983) estimated the seismic moment (M_o) of the 1886 earthquake to be 2.5×10^{26} dyne-cm, the fault rupture length 30 km, the rupture width 20 km, the average fault displacement 150 cm, the average static stress drop 50 bars, and the source rise time 8 sec. Because there was no conspicuous surface faulting, the lack of which is common for Eastern United States earthquakes, the focal depth must have been large enough so that the rupture did not extend to the surface. Using Talwani's (1982) interpration of the causative fault motion, the motion was right-lateral strike-slip on a plane striking N 26° E and dipping steeply to the WNW. Because the estimated rupture width for an M_S = 7.5 mid-plate earthquake is 20 km, because the fault plane is steeply dipping, and because there was no surface rupture, the minimum focal depth is considered to be 20 km.

OBSERVED EFFECTS OF THE 1886 EARTHQUAKE

The above description would have been of little immediate interest to those who experienced the earthquake. For them, the matter of death, injury and property damage was of much greater concern. I found two recent published estimates of the number of deaths attributed to the earthquake, one by Coffman et al (1982) of about 60, and the other by Steinbrugge (1982) of 110. Many people were reported injured, but no estimate of the number of injured can be found. Bolt (1978) reported property damage of $5,500,000 (1886 value), with 102 buildings destroyed in Charleston, 90% of the buildings in the city damaged to some extent, and nearly all of the 14,000 chimneys thrown down. Much of the above information was gleaned from McKinley's account in Dutton (1890), who reported an official death record of 27, but an additional 83 or more lives lost due to injuries, cold and exposure. McKinley noted that the number of wounded was never ascertained. Fire broke out immediately after the mainshock, but fortunately there was no wind to spread it. Although the inhabitants camped out for over a week, commerce resumed within two days, and the people soon tried to resume normal activities, as much as possible.

Manigault (Dutton, 1980) noted that the mainshock was preceded by several smaller tremors in the month of June, and some even before that. They were sufficiently strong to rattle sashes in the federal courtroom in Charleston, causing a disturbance similar to that produced by passing wagons or by a boiler explosion. At Summerville, which is about 15 km northwest of the epicenter of the mainshock (Charleston is about 25 km to the southeast) the foreshocks were felt at a higher intensity level. In particular, a boom-like noise was heard at Summerville, but not at Charleston, during the morning of August 27. A second shock was felt at both Summerville and Charleston at 4:45 a.m. (EST) on August 28, and during that day additional quakes were felt at Summerville.

The damaging mainshock occurred at 9:51 p.m. on August 31. Its duration at Charleston was estimated to be about 45 sec. Nine minutes later it was followed by a large, but distinctly less severe, aftershock. The epicentral region was a swampy pine forest, from which water and sand were extruded from the fissures in the soil. The damage to structures and the effects upon the inhabitants of Charleston have already been described. Dutton (1890) noted that there were numerous fissures in the soil of 1 to 2 cm in width and several meters in length over an area of 1500 km^2. Also, there were sand craters up to 6 m in diameter. He observed that "the most energetic and destructive (movements) came from a direction somewhat west of north", which is the direction towards the epicenter. Thus Rayleigh waves likely were responsible for the strongest ground motion at Charleston. Dutton noted, however, that many people also reported shaking which appeared to come from the southwest, which would correspond to Love-wave motion. The observers noted that the ground movement began gradually, accompanied by a roaring sound (P wave) and was followed by violent motion 10 sec later (S would have arrived 3 to 4 sec after P), which supports the idea that the most damage was caused by surface waves.

At Columbia, SC, and Savannah and Augusta, GA, each about 150 km from the epicenter, many buildings were damaged and a large number of chimneys were thrown down. Cracked walls, fallen chimneys, and floors broken loose from their supports occurred as far away as Charlotte, NC (250 km), and Asheville and Raleigh, NC (350 km). Similar but less extensive damage occurred as far away as Atlanta, GA (450 km). The area of structural damage had a radius of about 200 km, and the area of moderate damage had a radius of about 500 km.

The earthquake was felt in cities to the north and northwest as far away as 1300 km. To the east and southeast it was felt in Bermuda (1600 km) and Cuba (1200 km). To the southwest in the Gulf Coastal Plain it was felt only to 1050 km distance, reflecting the somewhat greater attenuation in the Gulf Coast area. Including the oceanic region, the felt area exceeded 5,000,000 km^2. Dutton (1890) noted, however, that at comparable distances the intensity was about 2 units greater for the 1811-1812 New Madrid earthquakes than for the 1886 Charleston earthquake.

Of particular interest was the many-times repeated observation that at large distances the intensity level was 1 to 2 units higher on the upper levels (3rd to 10th floors) than at the lower levels. At Cleveland, OH (1000 km) and Chicago, IL (1250 km) plaster fell from the ceilings of the upper floors of a few buildings, whereas the earthquake was only lightly felt at the lower levels.

EXPECTED EFFECTS OF A FUTURE 1886-SIZED EARTHQUAKE

The large population density and the vertical growth of the metropolitan areas of the Eastern United States will result in more severe and extensive damage for a future earthquake of $m_b = 6.6$ or $M_S = 7.5$ (the values assigned to the 1886 event) than experienced in 1886.

In order to approach the problem, I used some of my unpublished strong motion scaling relations for the Eastern United States, taking $m_b = 6.6$ and focal depth equal to 20 km. The peak horizontal (arithmetic average of the peaks of the two horizontal components) values of acceleration, velocity, and displacement can be estimated. The values are given in Table 1.

From Bollinger's (1977) reconstructed MM intensity map for the 1886 earthquake, after generalizing to remove local site effects, the outer limit of the X isoseismal is at a distance of about 20 km. For the IX to III outer limits, the values are 70, 200, 310, 480, 850, 1150 and 1300 km, respectively. If we accept intensity VIII as the threshold of structural damage, the corresponding ground velocity is 9.4 cm/sec. Taking intensity VI as the threshold of moderate or architectural damage, the corresponding peak

TABLE 1

ESTIMATED-PEAK GROUND MOTIONS FOR 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE

Epicentral Distance (km)	a_{max} (cm/sec^2)	v_{max} (cm/sec)	d_{max} (cm)
1	611	82.4	101
10	543	74.3	92.0
30	345	48.7	61.1
50	233	34.0	43.3
100	119	18.8	24.7
200	51.1	9.4	13.3
300	27.6	6.0	9.0
400	16.4	4.2	6.7
500	10.3	3.1	5.2
600	6.7	2.3	4.3
700	4.4	1.8	3.5
800	3.0	1.4	3.0
900	2.1	1.2	2.6
1000	1.4	0.9	2.2
1100	1.0	0.8	1.9
1200	0.7	0.6	1.7
1300	0.5	0.5	1.5

velocity is 3.3 cm/sec. At the higher frequencies and shorter distances associated with damage to structures caused by explosion-generated seismic waves, the ground velocity corresponding to the threshold of non-structural damage is 5 cm/sec (Duvall and Fogelson, 1962). Thus the numbers in Table 1 appear reasonable, because of the more prolonged duration of shaking and of wave frequencies closer to the natural frequencies of buildings for the earthquake-generated waves.

For the 1886 earthquake the motion of the 3rd to 10th floors of buildings at the fringe of the felt area (intensity = III) was about equivalent to intensity V shaking (falling plaster). This suggests an amplification of the peak velocity by a factor of about 2 1/2 at the upper level of the 1886 buildings. The present metropolitan areas have many buildings of 3 to 10 floors. For the upper floors of these structures, the shaking can be expected to be 1 to 2 MM intensity units larger than that shown by the generalized isoseismals of the 1886 earthquake. For the upper levels of the tall buildings (20 floors and greater), one might expect the shaking to be equivalent to that of 2 to 3 MM units larger than indicated by the generalized 1886 isoseismals. As an example, the upper levels of the tall buildings in New York City, Boston, Chicago and St. Louis likely will experience motion comparable to intensity V to VI from an $M_S = 7.5$ earthquake at Charleston. For similar buildings in Washington, D.C. the upper-level motion would be comparable to MM intensity VI to VII, and at Atlanta to MM intensity VIIIIX. We can conclude that the impact of the next large Charleston earthquake on the Eastern United States is going to be severe.

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PROBABILITY OF DAMAGING EARTHQUAKE GROUND MOTIONS IN THE EASTERN UNITED STATES

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INTRODUCTION

A number of probabilistic analyses of earthquake ground shaking in the Eastern United States have been published in the past seven years using a variety of seismic source zone models. Seismic source zone models based in varying degrees on the spatial distribution of historical seismicity and tectonic relations have been developed and used by Algermissen and Perkins (1976) and Algermissen et al (1982). McGuire (1977) has compared probabilistic MM intensities computed using the Algermissen and Perkins (1976) seismic source zones, source zones derived from a seismotectonic map of the Eastern United States published by Hadley and Devine (1974), and a model that considers the Eastern United States as a single source zone.

Research related to the origin of Eastern United States seismicity has, within the past several years, resulted in a number of new viable seismotectonic hypotheses regarding causes of damaging earthquakes. Evaluation of the consequences of these hypotheses in terms of both relative ground-motion hazard among various sites and absolute ground-motion hazard at individual sites provides an interesting perspective for the assessment of ground motion in the Eastern United States.

Evaluation of these new hypotheses requires the construction of seismic source zones models that correctly represent each hypothesis. It also requires the specification of other parameters such as upper bound earthquake magnitudes, attenuation, and rates of seismicity. As an initial effort, the following models have been selected for study.

Model 1: A single zone encompassing that part of the Eastern United States characterized by shallow Paleozoic detached structures.

Model 2: Two zones. The first outlines the early Mesozoic rifted terrane and the second zone characterizes the Paleozoic detached structures west of the Mesozoic rifted terrane.

Model 3: Same as Model 2 above, but with individual early Mesozoic basins (both known and inferred) delineated as separate sources.

Model 4: Broad zones representing a simple vertical movement model and accounting for areas of inferred regional positive and negative crustal movements.

For each of the models outlined above, seismic source zones were developed. A b value of 1.1 in the expression log N = a-b Ms was used together with an upper bound magnitude of Ms = 7.6. As an initial effort, probabilistic estimates of the maximum horizontal acceleration were computed at 19 representative points in the Eastern United States for exposure times of 10, 50, and 250 years with a 10 percent chance of exceedence. The acceleration attenuation curves of Schnabel and Seed (1973) modifed for the Eastern United States by Algermissen and Perkins (1976) were used in the computation of the accelerations. The earthquakes are assumed to be Poisson occurrences in time and are further assumed to occur randomly within each source zone.

Results of the probabilistic acceleration calculations for the four models described above were compared with the 1976 Algermissen and Perkins map values, the 1982 Algermissen et al map values, and the results of McGuire's (1977) analysis.

Preliminary results indicate little difference between ground motions resulting from models 1 and 2 above. For the early Mesozoic basin model (model 3 above), ground motions for points within the Newark-Gettysburg basin (for example, New York City) are about 30 percent higher than ground motions calculated at points between the basins (for example, at Boston, Massachusetts, and Philadelphia, Pennsylvania). For basins having only moderate levels of seismicity such as the Charleston-block basin that contains Charleston, South Carolina, ground motions are generally no different from points outside of the basins. Philadelphia, Pennsylvania; Boston, Massachusetts; and Charleston, South Carolina all have comparable levels of expected ground motions.

Comparison of acceleration values computed for a number of points in the Eastern United States using the four models described here, the Algermissen and Perkins (1976) model, and the Algermissen et al (1982) model indicates that with the exception of the Ramapo fault zone on the Algermissen et al, 1982 map, the probability of occurrence of 0.259 does not exceed 1 x 10-4 per year. If other acceleration attenuation curves are used (for example Nuttli, 1982) the annual probability of .25g are of the order of 1 x 10-3/year.

For the scale of zoning considered here the tectonic hypotheses considered, the configuration of seismic source zones selected for any probabilistic model appears to be less important than the attenuation function. Estimation of the levels of ground motion in the Eastern United States appears to depend much more on the attenuation function used than on the configuration of the seismic source zones at least for the scale of zoning used and the tectonic hypotheses considered here.

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IMPROVING HAZARD AWARENESS

by

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EARTHQUAKE HAZARD AWARENESS IN CHARLESTON

The specific problem of awareness of the earthquake hazard in Charleston is complex. From the survey of public administrators, local officials, planners, and insurance-real estate-banking representatives completed by Greene and Gori in 1981 (Greene and Gori, 1982), it is clear that there is a general popular awareness of the 1886 earthquake and the potential for local seismicity. It is also clear, however, that little of this awareness has been translated into the adoption of mitigation measures by governmental units, corporations, or households. The adoption of strategies to mitigate against the earthquake hazard requires more information from the scientific community concerning the location of the faults, the mechanisms causing seismic activity, probable recurrence intervals, and micro-zonation of areas particularly susceptible to ground failure. In addition, public officials and leaders in the private sector need to assess earthquake vulnerability in terms of (1) the identification of structures and critical facilities at risk because of a combination of location and structural characteristics; (2) the presence or absence of contingency plans to deliver immediate post-disaster services such as the provision of food, water and shelter on an emergency basis, fire protection, medical treatment, law enforcement, and other emergency assistance; and (3) the likelihood of economic recovery by various sectors of the community, given the combination of probable government assistance (local, State, and Federal) and private resources (earthquake insurance or community economic resources that might survive an earthquake). Such an assessment should lead to an understanding of the kinds of mitigation strategies that should be adopted. The next section will review what is known about increasing the likelihood of the adoption of these strategies.

AWARENESS, ATTITUDES AND BEHAVIOR

If there were a simple relationship between increased awareness of a hazard and the adoption of mitigation measures, many of us could fold up our books and go home. In such a situation, the seismologists could calculate the risk characteristics of a place, and then these data could be turned over to a public relations firm which could publicize the calculations on television or in a brochure. The population would have been duly warned, and would subsequently take measures to protect themselves against the impending event.

Unfortunately, the world is not that simple. Although the title of this presentation is "improving hazard awareness," what is implied is more than merely providing information - it is necessary that the information be heeded, and, most importantly, converted into a change in behavior.

The linkage between the provision of information and a change in behavior seems to rest on a model of voluntary adoption of mitigation measures: when information is provided concerning hazards, the attitudes of individuals are affected (they are more likely to believe there is a need for mitigation behavior), and subsequently will adopt mitigation practices. For example, then, a specific earthquake prediction (with time, place, and likelihood of occurrence specified), accompanied by information concerning feasible adjustment behavior will result in increased readiness on the part of the local population, who will then follow all or some of the suggested adjustment behaviors.

1.1 Information----------> Readiness/fear-------> mitigation behavior
(Attitude change toward environment by general population, corporations and government)

A vast amount of research in social psychology and communication has addressed the issue of this relationship between information and readiness (or attitude change (Saarinen, 1980; Baumann, 1980)). Baumann (1983) asserts that although many notification campaigns failed to persuade people to adopt mitigation measures, one can identify elements that seem to characterize successful efforts. These include:

1) Information should be specific to the resident's particular situation, for example, the location of the individual property with respect to the hazard should be indicated in the form of a map or verbal statement.

2) Information on both the costs and benefits of adoption/non-adoption of the mitigation measure should be provided - if one is trying to promote the adoption of building codes or earthquake insurance, it is necessary to cast this discussion in the framework of a specific cost-benefit analysis.

3) Information must be clear (unambiguous), and specify the kinds of strategies that can be adopted to mitigate the hazard.

4) The information source should be a credible one for the particular target audience and mutliple information channels should be used.

5) Social reinforcement of the information is helpful - communicate the idea that "everyone" is adopting these mitigation measures.

When these elements are present in an information campaign, there is a greater tendency for the information to be heeded, and mitigation measures adopted. Interestingly, in the case of the Illinois floodplain notification campaign, three different information programs each produced changes in knowledge and attitudes to floodplains as well as the adoption of flood damage mitigation measures. In addition, the least-costly program (a mailed brochure with accompanying endorsement letter) was as effective as the most costly (additional meetings of civic organizations, personal phone calls, mass media campaigns). This finding is significant in a context where it may be impossible to design complex and expensive information campaigns. This is not to say that a minimal effort-information campaign will be effective - rather that an information campaign which is carefully designed to apply principles of social science research, does not have to be complex or expensive to be effective, as long as the information is clear, geographically personalized, politically and socially personalized or endorsed, and costs and benefits of mitigation measures are provided (Baumann, 1983, p. 60).

EXTERNAL INCENTIVES

An alternative strategy to encourage mitigation against earthquakes in the absence of appropriate attitude-behavior relationships is the provision of external incentives. The word "external" here refers to the fact that the incentive for the adoption of a mitigation behavior lies not in the information-attitude-behavior complex itself, but is a motivation provided by an outside source, regardless of knowledge or attitudes concerning the hazard. External incentives include legislation requiring mitigation behavior (such as land use regulation and building codes) as well as other sorts of incentives (e.g. tax credits for mitigation measure adoption). In the case of Charleston, it is unlikely that land use regulation is feasible in the absence of detailed geologic information (Greene and Gori, 1982, 16), and in an area with a strong tradition of "privatism" in land use decisions. Similarly, some jurisdictions have not adopted any building code, or even where codes have been adopted, no one seems to inspect or enforce compliance (Greene and Gori, 1982, 17). State or Federal tax incenvites such as tax credits could be legislated, however, that would encourage such mitigation behavior as insurance purchase or investment in structural reinforcement. A cost-benefit analysis (the loss of revenue vs. the probable economic loss following an earthquake) would have to be calculated before it would even begin to be politically feasible to envision the adoption of such policies at a State level.

The point here is that while public information and the improvement of hazard awareness may be ends in themselves, it might be equally efficient to approach the problem of the adoption of mitigation measures by corporations and individuals through the use of external incentives. A model for this form of encouraging mitigation behavior is:

1.2	Scientific---> information	Readiness/fear---> (Attitude change toward environment by governmentor officals)	Government action---- (or market) provides positive negative incentives	Mitigation behavior

Although this model requires a certain degree of consensus to support legislation by local, State or Federal bodies, it is possible to achieve mitigation behavior even in the absence of universal attitude change.

Organizations, such as large corporations, may also adopt strategies which would enhance their own economic well-being, as well as the safety and economic security of employees. The adoption of mitigation measures by organizations may be analyzed as comparable to individual decision-making, although it is probably more instructive to look, additionally, at the competitive and collaborative nature of interorganizational networks, resource flows, power blocs, and political agenda of groups of organizations (Turner, 1981). Once the organization has made a decision with respect to the adoption of a mitigation measure, its impact on individual behavior will be widespread; however, the pre-adoption phase is complex, and fraught with the same irrational elements as the decision-making process so carefully studied for individuals and households (Turner, 1981).

DESIGNING A HAZARDS INFORMATION PROGRAM

Based on the findings of social psychological research, Vertinsky and Vertinsky (1982) have proposed a "matrix" or framework for communicating risk information. Earthquake hazards information campaigns in South Carolina can easily be planned using this table, given a specification of objectives and target audiences. I will try to summarize the Vertinskys' recommendations. First, the message itself (the content of the brochure or broadcast) must not only be accurate, but also contain "keystone" concepts that the audience uses for screening information - it should be based on the familiar and already-known. Second, the channel should be one which the audience will recognize as credible, since the channel itself may connote aspects of the message that may not have been originally intended. Third, it is important that the communicator can control the information channel, particularly if there is potential for conflict. Fourth, the form of the message should increase attention, and reduce possible misinterpretation. Fifth, the intensity of the message should be well-calculated - the intensity required for triggering action may differ from that required for long-term learning. One may not be able to attain both objectives at the same time.

The matrix itself is divided along the lines of (1) purpose of communication (e.g. risk information for regulatory processes, behavior modification, to improve cognitive skills for dealing with risks, to trigger action, crisis management, or alert), (2) the type of information (conceptual, action, general, technical, intuitive), (3) the target population (general public, decisionmakers), (4) channels (two-way interactive, direct-mass media, indirect - opinion leaders, formal-routine), (5) the message content, (6) the mode of presentation, and (7) the intensity and distribution. For example, if the goal is the communication of risk information for regulatory processes to direct attention, the type of information is intuitive, and the target population is the public at risk or opinion leaders, then the channel should be two-way interaction (seminars or task forces), the content should be the presentation of a conceptual framework, cost benefit tradeoff and a discussion of future possible scenarios, the mode of presentation should be concrete scenarios and dramatic display, the intensity should be low, and the distribution should be aimed at opinion leaders and mass media. I recommend to you careful perusal of this table for specific recommendations concerning communication strategies given other goals and audience types (Vertinsky and Vertinsky, 1981, pp. 471-3).

The findings of Baumann (1983) should give us reason for optimism - it appears that a carefully designed program of information dissemination can be carried out without excessive cost. What is needed is a set of decisions by local public officials as to what goals they would like to accomplish whether these be a heightened awareness of the danger and familiarity with mitigation measures, the adoption of specific mitigation measures, or a set of legislative decisions providing a set of incentives for individuals and organizations which will result in widespread adoption of earthquake hazard mitigation. Social scientists cannot decide on these priorities - but once they are set, can provide at least some guidance as to how the goals decided upon by community representatives may be fulfilled.

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THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE: A PROSPECTIVE ASSESSMENT

by

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INTRODUCTION

The rational preparation for a future earthquake in the Southeastern United States will depend upon developing a proper persepctive on the nature and extent of its impacts. This paper explores a sequence of events that could happen following a great earthquake in the region. The purpose of this paper is to present a possible future situation, not to represent that which is specifically expected to occur. While the author has attempted to be realistic in forming the estimate of future events, there is no representation that the events portrayed in this paper are expected.

The premise of this paper is that the earthquake has occurred. A policy making group is now meeting to set priorities for the response effort. Three basic areas are covered: information and communications, legislation, and the possible evacuation of a coastal region. For each of the "scenarios," the specific bodies that are to make decisions are identified. The presentation at the workshop was highly interactive. This aspect can not be captured in a written paper.

BACKGROUND BRIEFING ON THE EVENT

On Tuesday, 10 days ago, a massive earthquake occurred in South Carolina. It is reported to have a magnitude (m_b) of between 7.0 and 7.3 by the National Earthquake Information Service in Colorado. The earthquake was centered directly beneath Charleston, South Carolina. A preliminary analysis of the few strong ground motion recordings taken in the area, coupled with macroseismic observations, indicates that strong shaking lasted over 70 seconds, with a maximum effective acceleration of over 0.6 g. There have been numerous after shocks that are continuing to this very moment. The event has caused direct damage in eight states. The press characterizes it as the most severe natural disaster to have occurred in the United States during the life of the Republic. There is considerable consternation in political circles because the great earthquake everyone has expected in California happened here. Not withstanding the efforts of the Southeastern United States Seismic Safety Consortium, the public was generally unaware of its risk, and for all intensions and purposes unprepared.

Earthquake damage in the region can be characterized by three major observations. First, the damage to unreinforced brick structures, which have inherently little earthquake resistance, has been extensive; damage occurred as far as 300 miles from the epicenter. Second, there have been large scale soil failures at a scale not seen before in the United States. Third, the damage to lifelines is unprecedented. Lifelines are the electrical, water, sewer, communications and transportation systems that tie a community together and provide the services on which we all depend.

The Earthquake Engineering Research Institute reconnaissance team has made an estimate for the Federal Emergency Management Agency (FEMA) of the extent of damage. Figure 1 shows a first, highly preliminary, distribution of damage throughout the region. Roughly speaking the Modified Mercalli Intensities (MM) can be characterized as given in Table 1.

Preliminary assessments of the extent of life loss, injury damage and the extend of housing loss have been assembled from the three states hardest hit. Figure 2 reviews the basic situation in these three states. The loss of over 4,000 lives thus far, over 17,000 injuries that required hospitalization, the direct damage of approximately $25 billion and the loss of over 125,000 housing units are individually each the largest that peace-time emergency response organizations have had to cope with. Although these impacts are huge, they are considerably less than the first reports of $100 billion in losses and 25,000 dead.

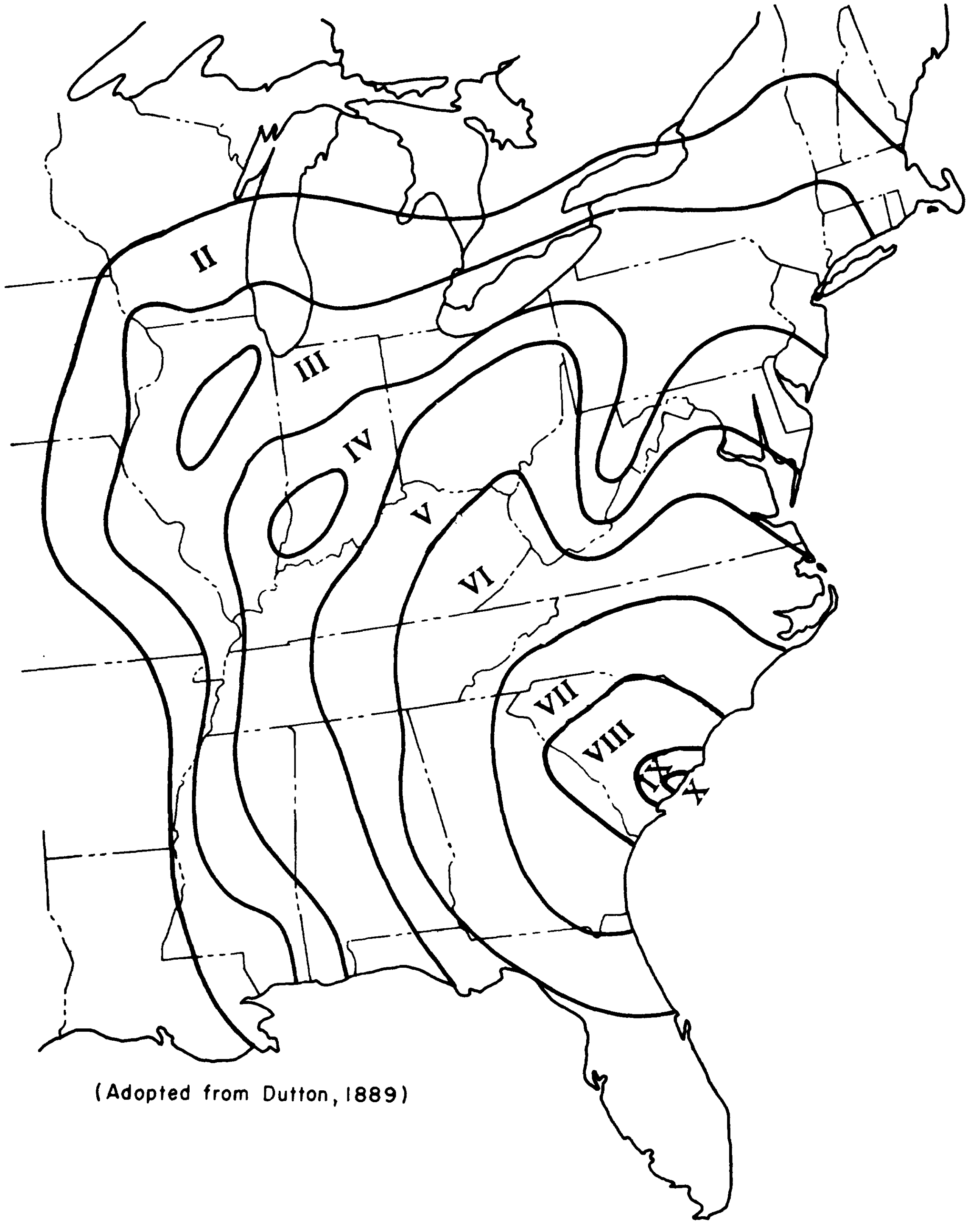
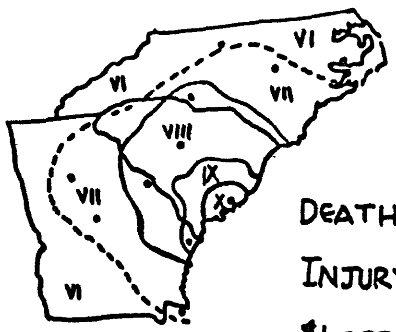


Figure 1.--Preliminary isoseismals for the Southeastern United States earthquake expressed in Modified Mercalli Intensitites.

Table 1 - The Modified Mercalli Intensity Scale (abstracted).

MM	Description
XII	Damage complete.
XI	Few if any masonry structures remain standing. Broad fissures in the ground.
X	Some well-built wooden structures damaged; most masonry and frame structures destroyed along with their foundations; ground badly cracked. Considerable landslides along river banks and steep slopes.
IX	Considerable damage in specially designed structures; well-designed frame structures thrown out of plumb. Buildings thrown off of their foundations. Underground pipes broken.
VIII	Damage slight to specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly build structures. Panel walls thrown out of frame structures. Fallen chimneys, factory stacks, columns, monuments and walls. Heavy furniture overturned.
VII	Everyone runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable to poorly built or badly designed structures.
VI	Felt by all; many frightened and run outdoors. Damage slight.
V	Felt by nearly everyone; many awakened. Unstable objects fall over; some plaster cracking.



IMPACT ESTIMATES

	SC.	GA.	N.C.	TOTAL
DEATH	3,225	640	415	4,280
INJURY	12K	3K	2K	17K
$LOSS	$16B	$5B	$3B	$25B
HOUSING	-85K	-26K	-16K	-125K

Figure 2.--Preliminary impact assessments for South Carolina, Georgia, and North Carolina

The President has declared Disasters in the entire state of South Carolina, most of Georgia and North Carolina, eight counties in Florida, six counties in Tennessee, two counties in Kentucky, two counties in Alabama and one county in Virginia. Several additional requests are still pending. All in all this is the largest declaration ever made. The resources of FEMA, state and local emergency response organizations, and supporting public relief organizations are being severly strained. Without the extensive use of military personnel, it is doubtful that any organized response would have been possible.

Damage has been particularly heavy to commerical, governmental and utility structures. Approximately two-thirds of the life loss and injury occurred within the MM X area. Most of the housing loss is concentrated in the MM IX and X regions. There has been damage to at least 10 earth dams in the epicentral area. Over 1000 chemical spills have been reported, most from storage facilities at manufacturing sites; the extent of water contamination and resultant health hazards is unclear. A preliminary assessment of impacts on lifelines indicates:

- All bridges to the coastal islands are damaged and unusable for regions within MM XI. Military bridges are in use but are insufficient in number and length. Hilton Head, Port Royal, Sea Island and St. Helena islands are isolated.

- Telephone capacity is at about 25% of pre-earthquake levels.

- Interstate highways are in limited service within MM VIII areas; blockages have reduce capacity to 33% of normal.

- Charleston airport is closed to non-military traffic. The Federal Aviation Administration (FAA) has restricted flights within the MM X area. Savannah airport is open and being operated by military personnel; there is limited commercial service. Columbia airport is open and has about 75% normal capacity. Fuel and services availability are limited.

- One rail line has been restored for limited use to Charleston from the north; all others are out of service. Savannah has two lines in service from the south, but no connections to the north.

- A petroleum pipeline through Columbia was severed as has been closed down. Natural gas pipelines within MM IX areas are all closed pending inspection; numerous breaks have been discovered. Local natural gas distribution within MM VIII areas has been curtailed.

- Electricity production in the region is now at 30% of the pre-earthquake level. It is estimated that 50% capacity will be restored within the year, with full restoration at least four years away.

- Electrical service has been restored to 70% of residential areas within MM VIII and to 30% businesses; traffic control and street lights are generally not functioning.

- Approximately 40% of the hospital beds within MM IX, and 15% in MM VIII are not available because of earthquake damage to hospitals.

- Wide spread damage has been done to the water distribution and sewer systems within MM VIII areas, with Charleston's and Savannah's water treatment plant destroyed. Safe drinking water is being supplied by the military. Estimates are that full service will not be restored for six months.

- The occurrence of large fires was moderate due to the unusually heavy rainfall in the previous few days.

The citizens' response in the impacted area has been outstanding. Generally the clean-up and recovery processes at the individual family level are well underway. The outpouring of assistance has been overwhelming. There has been a large inflow of people from unaffected areas offering help. Social scientists refer to this as "convergence." Initially, public response organizations were overwhelmed with these offers of aid. The convergence of people at sites of extreme need far exceeded the capacity for utilization; they initially impeded efficient response. This is now under control, in part, due to the imposition of restricted access by the highway patrol in the most severly affected areas.

The impacts on the financial community has been unprecedented. Among the most important are:

- The Atlanta Federal Reserve Bank computers have been down since the event. While this load has been partially picked up by other Reserve banks, the loss of data communications among member banks in the MM VII region has severly constrained the Federal Reserve Bank's ability to perform its commercial and regulatory functions.

- Standard and Poors Corp. has suspended the ratings of South Carolina, Georgia, and North Carolina municipal, special district, utility and selected business bonds. These bonds are widely held. Suspension has impaired their value, disrupted the market in tax exempt bonds and thrown into question the viability of several retirement funds.

- The financial condition of insurance companies within the region is uncertain. While there was little earthquake insurance written in the region, payments for medical costs, workman's compensation, business interruption, automobile damage, and professional liability are expected to be very large. The theory is already being advanced that earthquake damage should be covered by normal household insurance since the damage resulted from inadequate design and construction practices, not the earthquake itself. While this legal theory may sound far-fetched, it has been successfully argued in California for landslides, and was the basis for large payments to householders after the Coalinga earthquake even though their policies expressly excluded earthquake damage.

There are wide spread shortages of construction materials, equipment and skilled personnel. Costs for some materials has been bid up out of sight - particularly plywood. A large influx of potential construction workers from other areas is expected; although, there is little use for them now except for debris removal and clean up.

After presenting the workshop participants with this background information, specific issue briefings were presented. The participants were asked to consider themselves to be members of one of three groups. This was done to help them consider the policy problems presented from a specific, rather than general, point of view. The situation was then presented, followed by the policy decisions that must be made. Options were presented and a limited discussion of each from the floor was entertained before the participants were asked to select one of the options for action. The specific discussion is not given, however the results of the "voting" is.

INFORMATION COMMUNICATIONS

Each of the participants were assigned to one of the following group:

- An emergency services director at the local, state, or federal level;

- A television news reporter;

- A citizen of Georgetown, a community within the MM X damage area.

There has been a continuous flow of news reports on the earthquake. Most of these reports have been pictures of the damage and interviews with either eye witnesses or "experts" from undamaged areas. These "experts" have included some with knowledge or experience directly related to this earthquake; some who have special interests they are trying to advance using this earthquake as a target of opportunity; and, some with no knowledge of the area. "Factual" data from the damaged area is incomplete and often contradictory. The range of contradictory reports covers the need for medical transportation, the eminent collapse of dams, the contamination of water supplies, the extent of chemicals spills, fire occurrence, public health threats, building safety, and the imminence of large after shocks, to name but a few. The disaster intelligence functions of the FEMA and other emergency response agencies have been overwhelmed with the problem of trying to verify rumors and respond to the immediate demands of the press. Among the key problems leading to this condition are:

- Several key emergency reponse officials were killed or injured;

- Many counties have no organized response capability;

- Radio frequencies used by local fire, police and emergency response organizations are different among themselves and among adjacent jurisdictions;

- Unconfirmed reports are receiving wide spread media coverage; and,

- Reports are focused on individual observations.

As the social scientists are quick to point out, the conditions for rumoring are ideal:

- there are conflicting official reports;

- formal information channels are disrupted;

- there are preceived harmful effects; and,

- informal communications are heightened.

Four separate policies are under consideration.

1. The Department of Defense (DOO) should take charge of all the public communications capabilities of local, state and regional public response agencies.

2. The Federal Communications Commission (FCC) requires verification of electronic media broadcasts prior to their use. Compliance should be reviewed by __________.

3. Establish "rumor control" centers at sites within and outside the impacted area, especially where major reports are being generated. The centers should be coordinated by __________.

4. Communications systems should be widely distributed in the impacted area that operates on a consistent frequency. The system should be supplied by and paid for by __________.

Table 2 - Results of the straw poll on communications policy.
(no/yes)

Issue	EMS	Media	Citizen	Total	Action
1. DOD communications	16/20	13/18	12/25	41/63	Yes
2. FCC restrictions on media	26/9	26/5	24/13	78/24	No
3. Rumor centers	16/20	15/16	18/17	49/55	Yes
4. Distribute radios	12/23	14/17	17/19	43/59	Yes

Table 2 reviews the voting of the three groups; the first number in each pair indicates those against implementing the policy, while the second is the number in favor.

DISCUSSION:

It is interesting to note that freedom of the press was affirmed by a margin of only three to one. There was concern that the press was acting irresponsibly. A few suggestions were made to improve the situation. The scientific and engineering professional organizations could better organize themselves to provide easy access to well respected experts for interviews. The response agencies, particularly at the national level, could have an operational plan for meeting the media's needs, rather than leaving the media to develop their own sources. Of particular importance in the latter case is the coordination of statements by Federal agencies; they often feed the contradictory information process through differing press releases and public statements.

It is interesting that the placement of rumor control centers was only marginally endorsed. The establishment of such centers is a standard procedure of emergency management organizations. Such centers, when they receive a call, can trace the source of the rumor, establish its accuracy, and publicize, through the media, the true state of affairs on the specific issue. They are among the more successful emergency response undertakings. The only addition to standard procedure suggested was the establishment of such centers away from the impacted area. Their utility in reducing fear and correcting the misinformation that may make its way into the public discourse could be great. This is particularly important for events such as this, where policy decisions may be made by public and private organizations that have great impact on the community based upon information of dubious value.

LEGISLATION INTRODUCED

Each of the participants were assigned to one of the following groups:

- White House political staff;

- Director, Office of Management and Budget; and,
- Majority leaders of the House or Senate.

The political situation 10 days after the earthquake can be encapsulated in the following observations:

- There is a public information nightmare. The flow of information and misinformation to the public is staggering. The electronic media preempted there regularly scheduled programing and presented continuous, live broadcasts for the first days. Almost anyone who claims expertise has been given prominent coverage - both legimate experts and fortune tellers. As discussed above, rumoring is rampant.

- Approximately 40 Representatives and 15 Senators are demanding regular, personal briefings on the situation. Three Congressional committees have already scheduled hearings, with more in the offing. There is a regular military shuttle being run to show Congressmen and high Administration officials the damaged area.

- There are widespread reports that spilled toxic materials are just setting there with no efforts underway to clean them up.

- Over 100,000 people are reported to be isolated along the coast, particularly at the popular resort areas of Hilton Head and Sea Island.

- Over 40,000 are still housed in tents, and there is no apparent plan on how or when these people will be placed in more permanent housing. The blockage of many roadways is preventing importation of trailers; they are being set up far from the areas where people are who have need for them.

- There is confusion on whether there should be evacuation near the Oconee Nuclear Power Station. There are reports that damage was done to the containment structure. Actions thus far by emergency response officials range from attempted evacuation to assurances that everything is fine. The anti-nuclear groups are having a field day.

- Priorities among Federal agencies are unclear; staff and resources are not consistently assigned. A perfunctory review indicated that even with the consolidation of emergency functions under FEMA several years ago there are over 100 separate program responses under way.

- The Director of FEMA has resigned.

- A caucus of eight Senators and 35 Congressmen are publicaly calling for the President to exert direct leadership for response and recovery.

Even though the earthquake occurred only 10 days ago, legislation providing additional funds to the depleted disaster response fund has been enacted and signed into law. In addition the following bills have been introduced:

- ιo remove the requirement of 25% cost sharing by the state as a condition for Federal assistance.

- Reduce the Small Business Administration interest rate for reconstruction loans to 1%

- Increase the amount of individual family grants to $10,000.

- Repeal the Davis-Bacon Act so that artificially high wages need not be paid for clean-up and reconstruction.

- Eliminate minority contracting requirements.

- Increase the minority contracting set aside to 45%, matching the percentage of minorities in the impacted area.

- Wave payment of Medicare premiums for everyone in South Carolina.

- Provide Federal guarantees, after the fact, for state and local governmental bonds for those areas severely affected.

- Provide Federal reinsurance for private firms, ex post facto.

- Provide supplemental unemployment coverage, aid to dependent children, and welfare benefits.

This list is long and growing longer. There appears to be little constituency for restraint, and certainly none yet voiced at the national level.

Five policies are recommended to the President for consideration to help bring the political environment under control and assure the public that the national government is acting expeditiously. These are:

1. Appoint the Vice President as the Federal Coordinating Officer (FCO). If this is unacceptable, then appoint __________.

2. Hold a highly visible Presidential meeting at the White House with all the department and agency heads having response functions at which the President forcefully delivers instructions to spare nothing in providing aid to the impacted communities.

3. Restrict all current expenditures to emergency actions only.

4. Appoint a Presidential Commission to develop an integrated, economical redevelopment and recovery plan within ___ weeks.

5. Threaten to veto all legislation that is non-conforming with the Commission's plan.

Table 3 reviews the voting of the three groups; the first number in each pair indicates those against implementing the policy, while the second is the number in favor.

DISCUSSION:

The results of the voting were very surprising in that, with the exception of the Congressional response to vetoing non-conforming legislation, there was overall support for each of the proposals. It is particularly interesting that there was support for the Vice President being appointed as the FCO. As a general rule, public officials and agencies are rarely perceived as performing satisfactorily during such emergencies. This is no doubt caused by our overall desire to find the person who is to blame when things don't go right. It seems highly unlikely that the President would expose himself politically to such an evaluation of performance. In all likelihood he would appoint someone who could be dismissed. In this way the President could put distance between himself and the consequences of his appointment by removing the FCO if the situation should turn out badly, regardless of the level of performance of the appointee. This could not be done if the Vice President is the FCO.

Table 3 - Results of the straw poll on legislation policies.
(no/yes)

	Issue	White House	OMB	Congress	Total	Action
1.	Vice President as FCO	12/22	8/24	10/22	30/68	Yes
2.	White House Meeting	9/26	7/25	8/25	24/76	Yes
3.	Emergency aid only	9/26	2/28	11/22	22/76	Yes
4.	Presidential Commission	7/27	3/27	7/25	17/77	Yes
5.	Veto non-conforming bills	9/25	6/24	18/18	33/67	Yes

While the Presidential Commission was supported, it was surprising that the median response indicated that the report should be in the President's hands within four weeks, with many suggesting two. Commissions can seldom be appointed in such a short time, especially when so many interests could be helped or hindered by its outcome. Reconstruction and recovery are tricky problems where the formulation of poor policy could have huge consequences. It would be far better for the Federal government to formulate its policy options and needed legislation now, when there is both time and the imperative to be economically reasonable. Congress is much more likely to exercise restraint when presented with a whole package, than if they are given a bunch of pieces, that they might not think are wise to support but feel compelled to accept under the circumstances.

HILTON HEAD EVACUATION

Each of the participants were assigned to one of the following groups:

- Hilton Head Citizens Alliance;
- State of South Carolina's emergency services director;
- The Federal Coordinating Officer (FCO).

The National Hurricane Center has been monitoring the progress of Hurricane Charles for the past week. This hurricane is moving slowly and has been following an almost identical track to that of the devastating Hurricane Maude in 1921. Weather patterns appear to be the same regionally as observed then, see, thus they reasonably expect that it will follow the same path and strike the coast near the boarder between South Carolina and Georgia. Currently the Center estimates that it will strike in seven days plus or minus three days. Preliminary computer runs indicate that the storm surge will be 20 feet, or about 14 feet greater than the highest natural point on these coastal islands. The coastal islands have been completely cut off from the mainland by the all pervasive damage to bridges in the coastal region. Virtually all of the roadways to these islands are blocked as illustrated in. Hilton Head and Sea Islands in particular are at high risk. Hilton Head, the palce where Maude came ashore, is estimated to have a current population of 40,000. Many residents have stayed on after the earthquake. Construction there is mostly recent and well designed to resist wave forces - this provided good earthquake resistance for residential buildings. The Department of Defense estimates that it needs a minimum of three days to evacuate the population of these islands. The Center notes that using the best current methods, they cannot make forecasts of land fall with a greater than 25% accuracy three days in advance for the coastal segment between Jacksonville and Charleston.

Four policies have been recommended:

1. Recommended immediate evacuation of the coastal area.

2. Initiate evacuation when the probability exceeds ___%.

3. Use police powers to force evacuation if evacuation is initiated.

4. Withhold disaster assitance from those who refuse to evacuate when so ordered.

Table 4 - Results of the straw poll on Hilton Head evacuation.
(no/yes)

	Issue	Citizens	State	FCO	Total	Action
1.	Evacuate now	18/18	11/19	17/18	46/45	No
2.	Evacuate at ___%	4/31	0/30	7/28	11/89	Yes
3.	Use police powers	29/7	20/10	19/16	68/33	No
4.	With hold aid	33/3	20/10	28/7	81/20	No

Table 4 reviews the voting of the three groups; the first number in each pair indicates those against implementing the policy, while the second is the number in favor.

DISSCUSSION:

It was interesting that there was little support for evacuation unless there was 50% probability of a landfall within three days. This particular scenario is one of the most difficult because it forces participants to make large impact decisions in the face of a community that has already been hard hit. Part of the problem may be that the hurricane, however serious, seems small compared to the recent experience. It would be interesting to explore this behavior further, since it is clear that the regret would be great if the prediction is accurate and large life loss results.

The absence of an appetite for the use of police powers seems consistent with common political beliefs. It is doubtful that much encouragement would be needed for evacuation if an official call was made. It has been observed that people are more prone to take evasive action when they have recently experience in a similar event. Even without a call, it is likely that there would be substantial demand for evacuation assistance, since the area is issolated, as individuals evaluated the hurricane threat and concluded that the risk was high enough to cause them to act independently. It would be interesting to explore what the reactions might be if the potential event was not a hurricane, but the possible nuclear accident. Evacuation plans currently in place for nuclear power plants do not include, to the author's knowledge, the potential that another event may have precluded use of planned resources to affect an evacuation. It seems highly likely that in the charge post-earthquake atmosphere that a few anti-nuclear interests will play upon the situation and induce considerable public debate about whether evacuation is required to avoid the consequences of the potential contamination. Further, it is interesting to speculate how the introduction of the prediction of a large after shock might be treated. Such an event undoubtedly would be couched in probabilistic terms too. How decisions might be made for each of these cases is unclear to the author. Current preparedness plans do not seem to accommodate such situations. And it seems clear that trusting to luck that such situations will not arise or that they can be handled easily without preparations is unlikely to serve well.

The rejection of withholding recovery aid to those who did not evacuate is a confirmation that most people retain the belief that natural disasters are acts of God for which governments are an agent for recovery. This may not be good law, but it is probably realtistic politics.

AFTERWARD

It is now six months after the event.

Many of the initial impressions have been confirmed, while others have been changed. Table 5 reviews the loss statistics for the isoseismal areas of Figure 1 in the three hard hit states. Current estimates of the total damage are about $25 billion in direct damage. The Federal budget impact for the first year is estimated at about 12.5 billion. This is comprised of $6.5 billion in direct costs for debris removal, family grants, additional unemployment and welfare support, resource replacement, and repair grants to local governments and other institutions. The Department of the Treasury estimates that there will be a $5.5 billion revenue shortfall attributable to the earthquakes occurrence because of casualty loss deductions and lost income. As much as $10 billion may be made available under various low interest loan programs to families, business and governmental units.

Table 5 - Loss statistics by state and MM intensity.

	MM	SC	GA	NC	Total
Deaths:					
	X - XII	1990	--	--	1990
	IX	350	220	--	570
	VIII	810	190	180	1180
	I - VII	75	230	235	540
	Total	3205	640	415	4280
Housing Loss					
	X - XII	36K	--	--	36K
	IX	16K	10K	--	26K
	VIII	30K	7K	7K	44K
	VII	3K	9K	9K	21K
	Total	85K	26K	16K	127K

Among the notable events of the past six months are:

- The courts are clogged with claims for every conceivable cause. Some pundits have renamed this earthquake as the Great Lawyers Relief Earthquake of the Twentieth Century.

- Hurricane Charles veered off to the northeast and did not strike the continental United States

- A large after shock predicted by a noted European scientist failed to occur.

- The Department of Defense is demanding priority access to power, materials, and civilian personnel for defense contractors as the reconstruction process gets into full swing.

- 300,000 people were evacuated from the vicinity of the Savannah River nuclear processing plant when public concern reached an intolerable level based upon small releases of radioactive material and the threat of greater releases while repairs were underway. The decision was made more on political and public relations grounds rather than for technical concerns.

- 10CFR100, Part A, that specifies the earthquake resistance for licensed nuclear power stations, has been extended to all nuclear reactor facilities nationwide.

- The Director of the Office of Management and Budget, who was appointed the FCO, has declared that he is now ready for any assignment since he has survived being the FCO.

- The Presidential Commission is to report on its recovery plan in six weeks, on schedule. most jurisdictions are now well into the process of recovery, having not waited for the political wrangling to be completed.

- Congress acted to raise family grants to $10,000, arguing that the old figures didn't account for the inflation of the 70's and 80's.

- A damaging after shock that occurred six weeks after the main event increased the total damage by about 10%, but did not add appreciably to life loss.

- The competition for recovery funds is getting quite heated as the various interests jockey for advantage.

- The Governor of South Carolina lost his reelection bid three weeks after the earthquake. A major issue was the way the state responded and the fact that the state had failed to formulate an earthquake preparedness plan in spite of the repeated warnings from the Southeastern United States Seismic Safety Consortium. Prior to the event he was believed to have had a comfortable lead.

- Major new initiative to improve earthquake preparedness have been inititate by states in the Central United States and in the Puget Sound region without Federal prodding. Even California has stopped talking and started to act to improve its preparedness.

The tremendous energy exhibited by the local population has surpassed that expected. It is still to early to ascertain how well the affected area will recover.

POSTSCRIPT

This discussion has been purely hypothetical. Its purpose was solely to stimulte the reader to think about the problems posed by a massive earthquake in terms other than the direct damage. Time and time again, we have learned that we can not effectively respond to problems that have not been thought through prior to the need for immediate action. While emergency life and property savings functions are pressing and tax our resources, they are none-the-less straightforward. We know how to respond - only our lack of materials or management skills will prevent satisfactory action. The difficult problems are those where we cannot rely on our instincts or the goodwill of others. These are problems that have no simple solutions--indeed, they may not have one best solution at all. But our ability to recognize, diagnose and react to these complex socio-environmental issues is critical. This paper has attempted to start a process of examination that can bring these problems out into the open where they can be calmly and rationally discussed and functional relationships that lead to effective earthquake preparedness can be developed.

ACKNOWLEDGEMENT

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SUMMARY COMMENTS ON EASTERN SEISMICITY WITH EMPHASIS ON THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE-PROGRESS, PROBLEMS, AND COMPETING HYPOTHESES

by

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INTRODUCTION

The purpose of this session is to describe the important geological, geophysical, and seismological data that have enhanced our understanding of the causative mechanism or mechanisms of the 1886 Charleston, South Carolina earthquake. We also hope to delineate the lines of evidence that would be conclusive with respect to the selection of a particular causative mechanism (or mechanisms) for the Charleston earthquake. Over the past several years, the research programs in the Charleston area have vastly increased the geologic and geophysical data base on which the conflicting hypotheses are based. Yet, it is fair to say that the data base is not sufficient to allow the scientific community to reach a consensus regarding the causative mechanism(s) of this event. Many years ago, most of the community believed that the tectonic conditions in the Charleston area were unique, that is, that the Charleston earthquake could occur only in Charleston. As the research programs progressed, the concept of uniqueness came under increasing scrutiny until, at present, many people feel that the burden of proof has shifted such that it is now incumbent on those who want to say that Charleston is unique, to prove the uniqueness rather than vice versa. The uniqueness question has major societal implications particularly for the siting of critical facilities and, because of this, the answers are urgently needed. It is, I believe, the overall goal of this conference to shape the research programs of the immediate future to obtain the answers in the shortest possible time frame.

COMPETING HYPOTHESES

A nonexclusive and sometimes overlapping listing of hypotheses (and causative mechanisms) for the Charleston earthquake in particular and Eastern United States seismicity in general includes the following:

1) reactivation of pre-existing fault structures,

2) reactivation of Triassic or paleo-rift structures, border faults, etc.,

3) onshore extensions of oceanic fracture zones,

4) mafic intrusives (with or without serpentinization) as stress concentrators,

5) topographic highs and/or lows,

6) presence and absence of basin and dome structures,

7) movement along a decollement surface,

8) in the case of Charleston, activity of specific fault structures, and

9) movements along the edges of "block" structures 50-150 kms on a side (as delineated by gravity and magnetic data).

It should be noted that there may be multiple causative mechanisms for the intraplate seismicity under discussion. More importantly, it may be that none of the above hypotheses are correct. Each of our panelists today is an advocate of one of these models, but we do not have advocates for every possible model. The panelists will provide descriptions of some of these models and will hopefully outline the specific research required to prove the model in question.

PROBLEMS

1) The principal problems that we face here are not confined to Charleston. Very little is known about the causative mechanisms of intraplate earthquakes in general. For the entire Eastern United States (including Charleston, of course), no surface faulting that could uniquely be associated with earthquake activity has been identified. Much of the reasoning regarding possible causative mechanisms has, therefore, been inferential based on experience in the Western United States or in other parts of the world (but mostly from plate boundary areas).

2) The recurrence rates of intraplate earthquakes in general (and Eastern United States earthquakes in particular) are relatively low compared to plate boundary regions such as California.

3) Adequate instrumental monitoring of the eastern region has only been available for the past five to ten years. The results of this monitoring, in general, confirm the seismicity distribution inferred from historic, largely intensity data but allow, in a few instances, accurate delineations of source geometry.

4) The historic earthquake record is perhaps 300-400 years old, shorter than the proposed recurrence intervals of events like Charleston.

5) Society's demand for answers has outrun the immediate capabilities of the earth sciences community. In many siting decisions, earthquake predictions or accurate predictions of maximum expectable accelerations in 10^3, 10^4, 10^5, 10^6 years are expected. Can the community answer these demands?

QUESTIONS TO BE ADDRESSED

The questions that I would like to have these panelists address are, nonexclusively, the following:

1) Is there yet a preferred or a preferable model for the Charleston earthquake? (Alternatively, are all of the hypothetical models incorrect?)

2) How unique are any of the models (i.e. from a geological, geophysical, seismological, or tectonic viewpoint)?

3) From the current data base, what pieces of evidence are most conclusive?

4) Most importantly, what evidence (other than a similar earthquake at another Eastern United States location) would be conclusive regarding either the question of causative mechanism of the question of uniqueness?

TECTONIC MODELS - OLD AND NEW

by

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INTRODUCTION

In this paper, I will briefly review some of the existing models advanced to explain the seismicity near Charleston, South Carolina. I will offer alternative explanations for some of the observations and suggest experiments or studies to test them. Finally I will present a new model. This model, which I call the block tectonics model, is based on a variety of data and lines of evidence. Although each one of these has elements of speculation in it, ALL of them taken together make for a very attractive, geometrically coherent model. Actually they help to define what I will call the skeleton. The details--the muscles and the body are lacking, and I will suggest several studies designed to complete the picture.

BACKGROUND

The cause of the 1886 Charleston earthquake has been the subject of considerable debate ever since it occurred. Dutton (1889) examined the isoseismal data, and located two "epicentrum," in line with the then prevailing theory of Mallet. However, he refrained from speculating on the cause of the earthquake. Fortunately, the workers that followed Dutton were not so circumspect. Taber (1914) attributed the Charleston earthquake and the seismicity that occurred in the following 30 years to "readjustments taking place along a plane of faulting located in the crystalline basement underlying the Coastal Plain sediments, not far from Woodstock, and extending in a general northeast-southwest direction." This came to be known as the Woodstock fault.

Bollinger (1972, 1973a) described the historical seismicity (1754-1970) in the Charleston area as being a part of a diffuse NW-SE trending South Carolina-Georgia seismic zone (SCGSZ), dominated by the activity in the Charleston area. In search for a cause, Bollinger (1973b) compared releveling data of Meade (1971) covering the period 1915 to 1965 with the historical seismicity for the period 1920-1970. He noted, "that the differential crustal uplift data currently available does not explain some important aspects of the region's seismicity, most notably, the concentrated activity near Charleston, South Carolina."

In 1974, the USGS began a multidisciplinary effort at understanding the cause of the seismicity at Charleston (Rankin, 1977). Several authors noted as apparent correlation between the NW-SE diffuse SCGSZ and the orientation of the Blake Spur Fracture zone and suggested possible causal association (Sbar and Sykes, 1973; Talwani and Howell, 1976; Fletcher et al., 1978; Sykes, 1978).

The results of COCORP deep reflection survey in Georgia suggested that much of the SCGSZ was allochthonus and had been thrust northwestward several hundred kilometers (Cook et al., 1979, 1981). Harris and Bayer (1979) claimed that a similar feature existed in Virginia. The interpreted depth to the bottom of the decollement near Charleston is 10-12 km, which is the depth range of the observed seismicity (Tarr et al., 1981). Although the extent of the decollement is seriously questioned (Long, 1979; Hatcher and Zeitz, 1980; Iverson, 1982) its inferred presence near Charleston has spawned two new models with far reaching consequences.

THE MODELS

The models postulated to explain the observed seismicity can be broadly divided into two classes--mechanistic and structural. In the former, a mechanism is suggested without specifying the geologic feature responsible. Taber's (1914) readjustments in the crystalline basement and Bollinger's (1973b) attempt to explain the seismicity by differential crustal uplift, fall in this category. These will not be pursued any farther.

The structural models have evolved since the start of the Charleston project in 1974. These fall into three categories. In the first, "stress amplification near plutons," it is suggested that seismicity is associated with certain intrusive bodies. These models are based on the spatial association of observed seismicity with the location of these bodies. In the second category, earthquake activity is directly or indirectly related to the postulated omnipresent decollement. In this category, the main causative feature is essentially a deep (∿10-12 km) buried horizontal surface. In the third category, movement is associated with steeply dipping faults in this category, the causative feature is essentially vertical. I will discuss each of these models and suggest possible tests.

STRESS-AMPLIFICATION NEAR PLUTONS

The observed spatial association between gravity highs (interpreted as mafic plutons) and local seismicity was the basis of a suggestion that the two are related (Long and Champion, 1977; Kane, 1977; McKeown, 1978; and Barstow et al., 1981). The proposed mechanism (Kane, 1977; Long and Champion, 1977) required a large difference in the coefficient of rigidity of the materials making up the plutons and the surrounding rocks. Campbell (1978) calculated the local stress concentration to be a factor of two increase for strong intrusive bodies and up to a factor of 9 increase for weak intrusive bodies.

Even if such diversity in rock properties was available (although available data do not suggest this), the existence of a large number of plutons without associated seismicity argue against stress amplification of buried plutons as being the causative mechanism. However, there is another possible explanation for the observed spatial association of buried plutons and seismicity. These plutons are symptomatic of a zone of weakness in the earth's crust, i.e. the plutons rise where there was an existing weakness in the earth's crust, thus any seismic response to the earth's stress field would be at these loci of weakness. In conclusion, the spatial association appears to be valid, however, the postulated mechanism may not be.

I suggest further modeling, using realistic parameters for the in situ stress, elastic constants, etc. Also, in areas where the tectonic picture is better understood, check if the location of plutons is in any way related to known major crustal features.

REACTIVATION OF THE DECOLLEMENT

Behrendt et-al. (1981), identified a northeast-trending zone of high angle faulting near Charleston based on seismic reflection profiling. They termed the zone, the Cooke Fault, and identified 50 meters of downdrop on the southeast side, which they tentatively interpreted as being a Cenozoic reverse fault. By extending the fault upward it coincides with an area where a cluster of earthquakes occurred from 1973 to 1978. They suggested that this fault may be causally related to those earthquakes several km below. Moreover, Behrendt et al. (1981) identified the Helena Banks fault, 12 to 25 km offshore. This is a high-angle reverse fault, striking northeast, 60 km in length, and displaces sediments within 10 meters of the sea bottom. Behrendt et al. (1981) interpret that the northeast striking, high-angle reverse faults are produced as second-order conjugate shear faults in response to slip along the decollement of Cook et al. (1979,1981) and Harris and Bayer (1979). They further interpret that this slip is caused by active regional compression in the Charleston region baseu upon the stress provinces defined by Zoback and Zoback (1980).

Many investigators believe that reactivation of basement faults from Precambrian to Mesozoic age resulted in slip which produced the 1886 Charleston event. Wentworth and Mergner-Keefer (1981) have interpreted that most Cenozoic reverse faults of the Atlantic margin "probably follow older discontinuities, especially early Mesozoic normal faults...". They infer that the Charleston event probably had a reverse-fault origin and cite Behrendt et al. (1981) as evidence of the Cooke and Helena Banks faults, discussed above.

Some of the problems with this model are listed below.

a) The existence of a master decollement underneath the Coastal Plain is not established. Also it implies that the buried Triassic basins are not rooted.

b) The inferred orientation of the maximum horizontal stress axes, NW-SE, is not supported by the fault plane solution data near Charleston.

c) The seismicity is deeper than the depths of the inferred Cooke fault.

d) The pattern of relocated earthquakes is at variance with the location of postulated faults.

e) Concentration of seismic flux in the Charleston area suggests that the current seismicity is not aftershock activity of the 1886 event, but an indication of a local center of activity.

I suggest the following series of tests.

a) Reinterpretation of accumulated reflection data with better velocity data.

b) It is important to get a better handle on the orientation of the in situ stress field. I recommend additional hydrofracture measurements in the crystalline rocks, e.g. in some new wells and use of other methods of obtaining fault plane solutions, such as use of SV/P ratios, and from spectral data.

c) Compare the observed seismicity pattern (fault plane solutions, depths, etc.), geology and tectonic setting with other regions where there is evidence of decollement surfaces.

BACKSLIP OF A MASTER DECOLLEMENT

This model is based on an interpretation of the reported effects of the Charleston earthquake, the postulated existence of a master decollement surface below the Coastal Plain, and from an interpretation of possible temporal relationship of the 1886 event with some sounds (interpreted as microearthquakes) heard in the Piedmont several months before it. According to the model proposed by Seeber and Armbruster (1981), backslip of the decollement surface due to gravity over an area covering most of South Carolina, can explain the observed intensity effects of the 1886 event.

Some of the problems with this model are listed below.

a) The existence of the master decollement under the Coastal Plain is not established.

b) There are other possible explanations of the observed intensity data. The pattern of intensity for the Nov. 22, 1974, M_L 3.8 event was remarkably similar to the 1886. The former was instrumentally located at Middleton Gardens.

c) The "foreshocks" at Ninetysix cited as evidence of a large area becoming active can be explained as being local features associated with massive plutons, much as the current seismicity near Newberry, South Carolina)

d) The mechanics of moving such large land masses imply the presence of extremely high pore pressure over large areas together with universally low coefficients of friction (<.05), and it is unclear how these land masses would ride over perturbations at the edges of basins, etc.

e) The orientation of the principal stress axes used by the authors (NW-SE for σH_{max}) is at variance with those inferred from fault plane solution data.

To test this model, I suggest:

a) Simple models to test if this model is mechanically feasible.

b) Comparison of tectonic regimes where the analogs are suggested--to see if these analogs are applicable.

c) Simple models to show if the wedge shape of the Coastal Plain can be instrucmental in focusing seismic energy along the fall line--as suggested by the observations.

SEISMICITY ALONG THE SCGSZ - AND INTERSECTING FAULTS

The northwest trend in historic seismicity in South Carolina (Bollinger, 1972, 1973a) was labeled by him the South Carolina - Georgia Seismic Zone (SCGSZ). This apparent trend is also preserved on relocated instrumentally recorded earthquakes (Dewey, 1983). There is considerable debate (a) if this NW zone exists and, (b) if it does, to what extent? Tarr et al. (1981) suggest that clustering in the Coastal Plain is along the SCGSZ and diffuse in the Piedmont. Earlier workers (Sbar and Sykes, 1973; Talwani and Howell, 1976; Fletcher, et al., 1978; Sykes, 1978) noted that the SCGSZ may be related to the offshore Blake Spur fracture zone (BSFZ). However, lack of a convincing argument for its existence and for an extension of the BSFZ to the NW, especially onshore, impeded its acceptance. The identification of buried Triassic basins under the Atlantic Coastal Plain led Talwani (1979) to suggest that the seismicity in the South Carolina Coastal Plain and in the Central Virginia seismic zone was occurring at localized zones of weakness formed at the intersection of an older preexisting zone of weakness (PZW) (e.g. the extension of BSFZ in South Carolina and Norfolk fracture zone in Virginia) and boundary faults of Triassic basins. Relocation of instrumentally located earthquakes in the Charleston area (1974-80) led to the delineation of two possible intersecting faults (Talwani, 1982). The shallow NW trending Ashley River fault appears to be related to the BSFZ. However, further development of this model required identification of onshore extension of BSFZ.

THE BLOCK-TECTONICS MODEL

We have used several lines of evidence to suggest a block tectonics model to explain seismicity in Southeastern U.S. These include offsets in trends of aeromagnetic and gravity anomalies, distribution of seismicity and possible causative faults, fault plane solutions, detailed gravity profiling, geologic mapping, location of gold and other minerals, density of dike activity, geomorphic data, etc. These data, together with the delineation of Lake Erie--Maryland block by Lavin et al. (1982) and the eastern Kentucky block by Mathews (1982), have been combined to formulate the block tectonics model. This model will be presented at the Spring meeting of the AGU, next week, and the abstract of that paper is included as an Appendix.

Some of the problems with this model are listed below.

a) Most structural trends have been interpreted from other data--direct evidence of blocks is lacking.

b) Age relationship of various tectonic features has not been established.

c) The depth extent of various tectonic features has not been established.

d) There is a need to check the validity of the data used in formulating the model e.g., potential field, seismic, mineral locations, etc.

e) Are there other locations of intersecting structures--especially in an intraplate setting?

To test this model, I suggest:

a) Detailed gravity, magnetic and seismic reflection studies designed to delineate targeted structures (parallel New Madrid).

b) Reinterpretation of seismic reflection data (including Seisdata line 4) with improved velocity data.

c) Shallow boreholes (∿500 m) to obtain geologic evidence for postulated faults.

d) Seek analogs elsewhere (of intersecting structures).

e) Seek evidence of these blocks in Africa.

f) Look for other indirect lines of evidence, e.g.

   1) Sedimentary structures (e.g. in Pa.)
   2) Metallogenic zones.
   3) Density of dike activity.
   4) Landsat data.

g) Regarding fault plane solutions

   1) Incorporate additional seismic data since 1980.

   2) Fault plane solutions by using SV/P and spectral techniques.

h) Model observed surface effects (deformation of railroad tracks) to see if they are compatible with fault plane solutions derived from current seismicity.

i) On a regional scale need to incorporate a variety of data regarding

   1) Concept of Suspect Terranes.

   2) Coherence in pattern of seismicity in East Coast.

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APPENDIX

A BLOCK TECTONICS MODEL TO EXPLAIN SEISMICITY IN SOUTHEASTERN UNITED STATES

by

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The earliest models suggested that seismicity in Southeastern U. S. occurs on NW oriented preexisting zones of weakness, possibly associated with oceanic fracture zones. However, evidence for such onshore features was not recognized. We have examined a variety of data which has enabled us to identify these features, which appear to be associated with observed seismicity. These observations are incorporated in a block tectonics model. We propose two major NW-SE trending blocks, 60-70 km wide and several hundred km long, associated at their SE termini with oceanic fracture zones. The Blake Spur fracture zone (BSFZ) block can be traced NW through South Carolina to the Brevard zone, where it appears to be offset to NE. It continued as the Eastern Kentucky block, which waa recently recognized by Mathews (1982). The Norfolk fracture zone (NFZ) block can be traced through Virginia, West Virginia, and possibly Pennsylvania where it has been termed the Lake Erie-Maryland block by Lavin et al. (1982). Both blocks exhibit evidence of NW and NE movements. The NW movement ($\sim$40-60 km) is inferred from offsets in aeromagnetic anomalies, and NE movement on BSFZ block is inferred from right lateral offsets ($>$ 40 km) on the Modoc and Brevard faults. The intersection of the BSFZ block with Triassic boundary faults and the Kings Mountain belt in South Carolina, an unnamed major NE feature in SW Virginia identified by Bollinger and Wheeler (1983), and the Hickman fault zone in Kentucky define the location of seismicity near Summerville, Bowman, and Union County, South Carolina Giles County (1897) and Sharpsburg County, Kentucky (1980), respectively. The intersection of the NFZ block with a Triassic basin defines the location of seismicity in central Virginia.

(Note: Presented at AGU/Baltimore, May 31, 1983.)

THICK VS. THIN-SKIN MODELS FOR NEOTECTONICS IN THE APPALACHIANS

by

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Recently, long-standing assumptions about earthquake hazard in the Appalachian region have been questioned. The urgent need to improve constraints on the earthquake hazard in the Southeast has focused the attention of earth scientists on this intraplate region and is partly responsible for the proliferation of models proposed to account for its neotectonic activity. The diversity of recently proposed models attests to our meager knowledge about the operative tectonic mechanism but is symptomatic of new ideas and new data which will inevitaly produce better constraints on the earthquake hazard in the Appalachian region.

Some of the proposed models are not mutally exclusive. In particular, none of the models (e.g., Pomeroy, Charleston workshop, May 1983) are necessarily inconsistent with a detachment reactivation model, in which slip on Paleozoic detachments is the fundamental cause of Appalachian neotectonics (but not necessarily the source of the earthquakes). Structural features within the slabs above the detachments (such as Triassic normal faults, Paleozoic listric thrusts, vertical faults limiting large blocks and possibly associated with oceanic fracture zones, igneous bodies as stress concentrators, Cenozoic basins or uplifts and other reactivated zones of weakness or of high stress) may or may not be associated with neotectonic activity and seismicity that result from slip on underlying detachments.

Thus, we can identify a thick-skin model, or family of models in which stress and strain are, in the first approximation, continuous through the lithosphere, and a thin-skin model in which stress and strain are decoupled at some subhorizontal detachement (Figure 1). In the absence of contrary evidence, a thick-skin model is preferred because it is simpler and because slip on large subhorizontal faults seems unlikely from a rock-mechanical

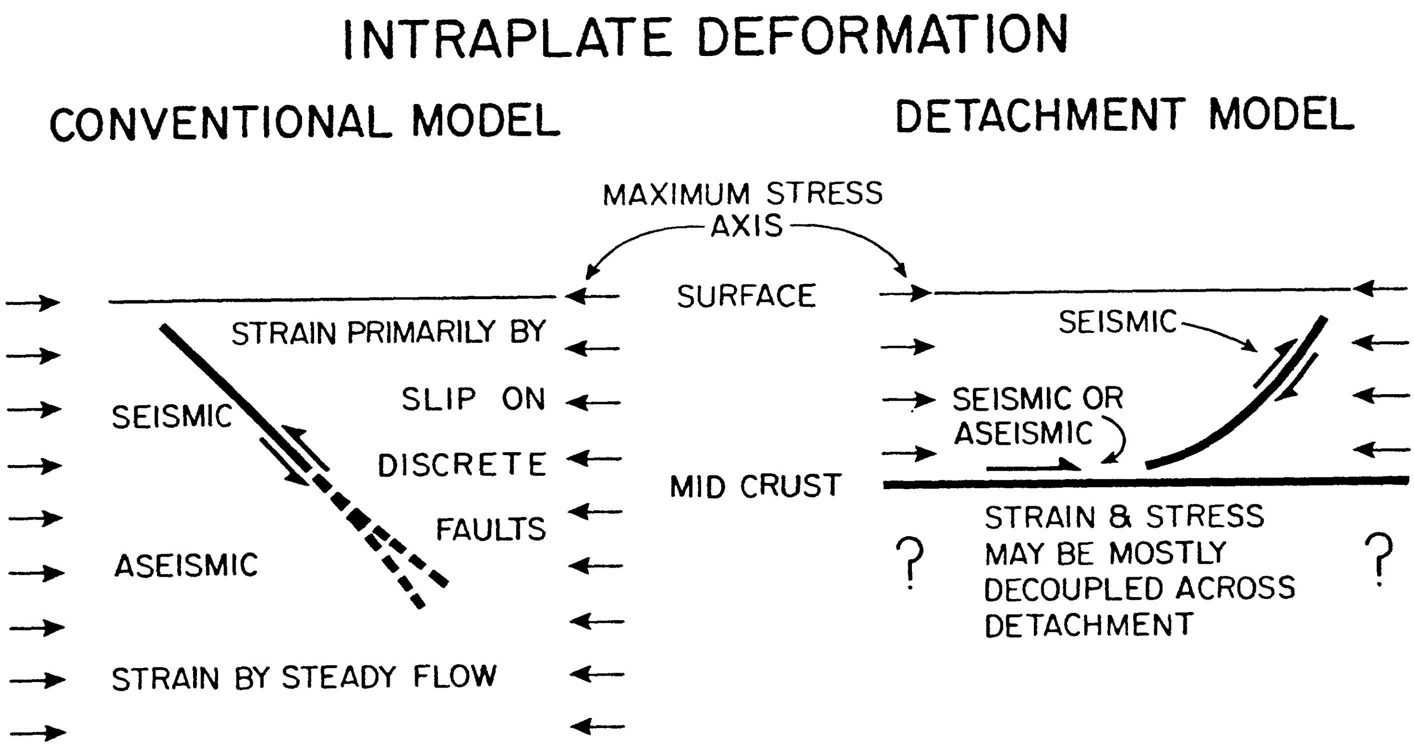

Figure 1.--Two models for intraplate neotectonics along the Appalachians, including the Atlantic seaboard. The thick-skin model (Wentworth and Margner-Keefer, 1983) could not account for wide-spread bursts of seismicity over an area much wider than crustal thickness, whereas the detachment or thin-skin model could account for such bursts by aseismic slip events on large portions of the detachment. The late Paleozoic detachment associated with a major continental colision events appears to be very extended along and across strike (e.g., Cook et al. 1981). The detachment was appaprently not cut by Mesozoic rift faults and may be still an effective decoupling layer (Seeber and Armbruster, 1981).

standpoint, particularly in view of post-orogenic annealing of fault zones by recrystallization at mid-crustal depths.

Accordingly, in the evolution of geological thought a thick-skin model has always been the first assumption. The thin-skin nature of many convergence zones, however, has now been demonstrated by surface and subsurface data (e.g., Paleozoic Appalachians; Paleogene Canadian Rockies; Neogene Himalayas). More recently, thin-skin deformation has been found to play an important role in zones of continental extension (e.g., Mesozoic Appalachians; Neogene Basin and Range province).

The Southeastern U.S. is the first intraplate region for which a thin-skin model of neotectonics has been proposed. The evidence so far is weak and indirect. It includes large and widespread deformation in the Coastal Plain of South Carolina coseismic with the 1886 earthquake (Seeber and Armbruster, 1981); apparent lack of major vertical offsets of Paleozoic detachments (e.g., Cook et. al., 1981) and of the Cretaceous unconformity at the base of the Coastal Plain wedge (e.g., Hamilton et. al., 1983); seismicity limited to the slab above the Paleozoic basal detachment in the Virginia seismic zone (Costain, Charleston workshop, May 1983) and possible post-Jurassic westward tilt of the Piedmont (Dooley and Smith, 1982).

Finally, the non-systematic correlation between structural features and seismicity along the Appalachians may also be considered indirect evidence for detachment reactivation. In a time-stationary model, a structural interpretation of seismicity has been elusive. This suggests a time-varying model in which current seismicity is a snapshot view of a pattern changing on a time scale longer than historic time. Recent results indicate widespread changes in southeastern seismicity associated with the 1886 earthquake and support this model (Seeber and Armbruster, Charleston workshop, May 1983). In analogy to seismicity patterns along plate boundaries, widespread changes in the distributions of seismicity in intraplate regions may be associated with large tectonic events, which need not be seismic, but would require slip on large faults. Subhorizontal crustal faults are the largest known structural features in the Appalachians and seem the most likely locus of such events, particularly since we find no evidence for large (½ 100 m) Neogene movements on any single steeply-dipping fault or group of faults.

A thin-skin neotectonic model for the Appalachians, however, also presents a number of problems:

1) Some of the evidence in favor of detachment-slip apply to the Coastal Plain of the southern Appalachians, but the "master detachment" of the Appalachians may not extend further southeast than the Inner Piedmont (e.g., Iverson and Smithson, 1982; Cook, 1983) although prominent mid-crustal shallow-dipping faults, such as the deeper part of the Augusta fault, have been identified in this area (e.g., Cook et. al., 1981).

2) The direction of maximum horizontal compression seems to be NE in the Piedmont from hydrofracture measurements, (e.g., Zoback, at the May 1983 Charleston meeting) and in the Charleston area from fault plane solutions (Talwani, 1982). Back-slip on the detachment terminating downdip near the Coast (Seeber and Armbruster, 1981) would probably require a post-event NW compression in this area.

3) If detachment dip-slip has been consistently in the same direction over some geologic time, considerable strain must be accumulated in the detached slab at the up-dip and down-dip end of the active zone. Evidence for such strain in the Cenozoic has not been reported, but neither has much effort gone into looking for it.

4) The movement of wide crustal blocks over shallow-dipping Appalachian detachments require a very low coefficient of friction on these Paleozoic faults, particularly if the driving force is gravitational, and may be mechanically unfeasible. Although these and other objections to the thin-skin model have not been satisfactorily answered, most of the community seems to weigh the evidence in favor of this model sufficiently to give it careful consideration.

Thin-skin tectonics does not preclude most of the other proposed models and may provide the fundamental kinematic and stress conditions regulating deformation in the upper crust. Under thick-skin conditions in which the causative stress is uniform along the Atlantic seaboard, if a particular steeply-dipping fault in the upper crust were found to be the source of the 1886 earthquake, all similar faults along this margin would be potential sources for 1886-like earthquakes (e.g., Wentworth and Mergner Keefer, 1983). On the other hand, if Appalachian neotectonics is thin-skin, large-scale slip events on the mid-crustal decoupling zone might generate the stress concentration in the upper crust causative of seismogenic slip on more steeply dipping faults. In this case, the likelihood of rupture of an upper-crustal fault would depend on the history of slip on the underlying detachment. Thus, the key to earthquake hazard estimates in a thin-skin environment is understanding the slip behavior at the detachment, as has been amply demonstrated along plate boundaries.

In conclusion, the evidence for thin-skin intraplate neotectonics in the Appalachians is inconclusive but sufficient to warrant a concerted effort to test this hypothesis. If the hypothesis of thin-skin neotectonics is entertained at all, it should be tested first since the result would substantially determine subsequent strategies to test more specific hypotheses for seismogenesis and to infer earthquake hazard.

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1886-1889 "AFTERSHOCKS" OF THE CHARLESTON, SOUTH CAROLINA, EARTHQUAKE: A REGIONAL BURST OF SEISMICITY

by

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INTRODUCTION

A successful model for intraplate tectonics and a reliable estimate of earthquake hazard along the Atlantic coast province depends to a large extent on a better understanding of the 1886 earthquake in South Carolina. Most of the constraints on this pre-instrumental event have been obtained from the effects of the main shock (Dutton, 1889; Everndon, 1975; Bollinger, 1977; Seeber and Armbrustor, 1981). Results from geologic and geophysical exploration for active structures in the 1886 source region have been suprisingly negative and allow for different interpretations (e.g., Tarr, 1977; Behrendt and Hamilton, 1981; Wentworth and Mergner-Keefer, 1981; Talwani, 1982). Large-scale patterns of seismicity can be clearly discerned in the current catalog of southeastern earthquakes, but the evidence for strong bias in parts of this catalog is equally obvious (Seeber et. al., 1982). This study originated from the idea that the space-time distribution of seismicity associated with the 1886 main shock could be studied with new data and that it could provide important new constraints on this event and on the mechanism for intraplate tectonics along the Appalachians.

In this paper we present new results on seismicity in the Southeastern U.S. obtained from newspapers for the ≈3 1/2 years including and following the 1886 Charleston earthquake. The main purposes of this work are to:

1) Improve constraints on the 1886 aftershcck sequence.

2) Test newspapers as source of earthquake data in the preinstrumental period.

3) Develop a systematic approach that would maximize uniformity and completeness in an earthquake catalog extracted from a network of newspapers.

SOURCES, METHOD AND DATA

The new earthquake data presented here cover South Carolina, Georgia and North Carolina during 1886-1889. These data were obtained by a two-phase search of contemporary newspapers in that area. In the first phase we scanned every issue of 6 of the 9 available dailies in that area. In the second phase we searched all available newspapers for every event we had discovered. This systematic approach can insure a relatively complete and uniform coverage without a prohibitive effort. After scanning ≈7,000 issues of 50 different newspapers we have obtained ≈3,000 felt reports and identified 470 earthquakes to which we can assign an approximate location and magnitude. Previous catalogs list ≈135 events in the same time and space. Of these, 65 are listed in our catalog. The remaining ones are either small and/or reported only by one person in Charleston/Summerville, or earthquakes from the first 12 hours of the aftershock sequence when individual events cannot be reliably distinguished.

Epicenters are assigned from the intensity distribution. For the purpose of evaluating their reliability, we classify the earthquakes in 4 categories:

1) Single-town events of intensity II or reported by a single individual, or otherwise doubtful.

2) Single-town events of intensity>III felt by many people which can be clearly recognized as earthquakes.

3) Multitown events with an epicentral zone well defined by either a bull's-eye pattern of increasing intensities or by a tight cluster of felt reports (e.g., Figure 1).

4) Multitown events with similar intensity level over a wide area.

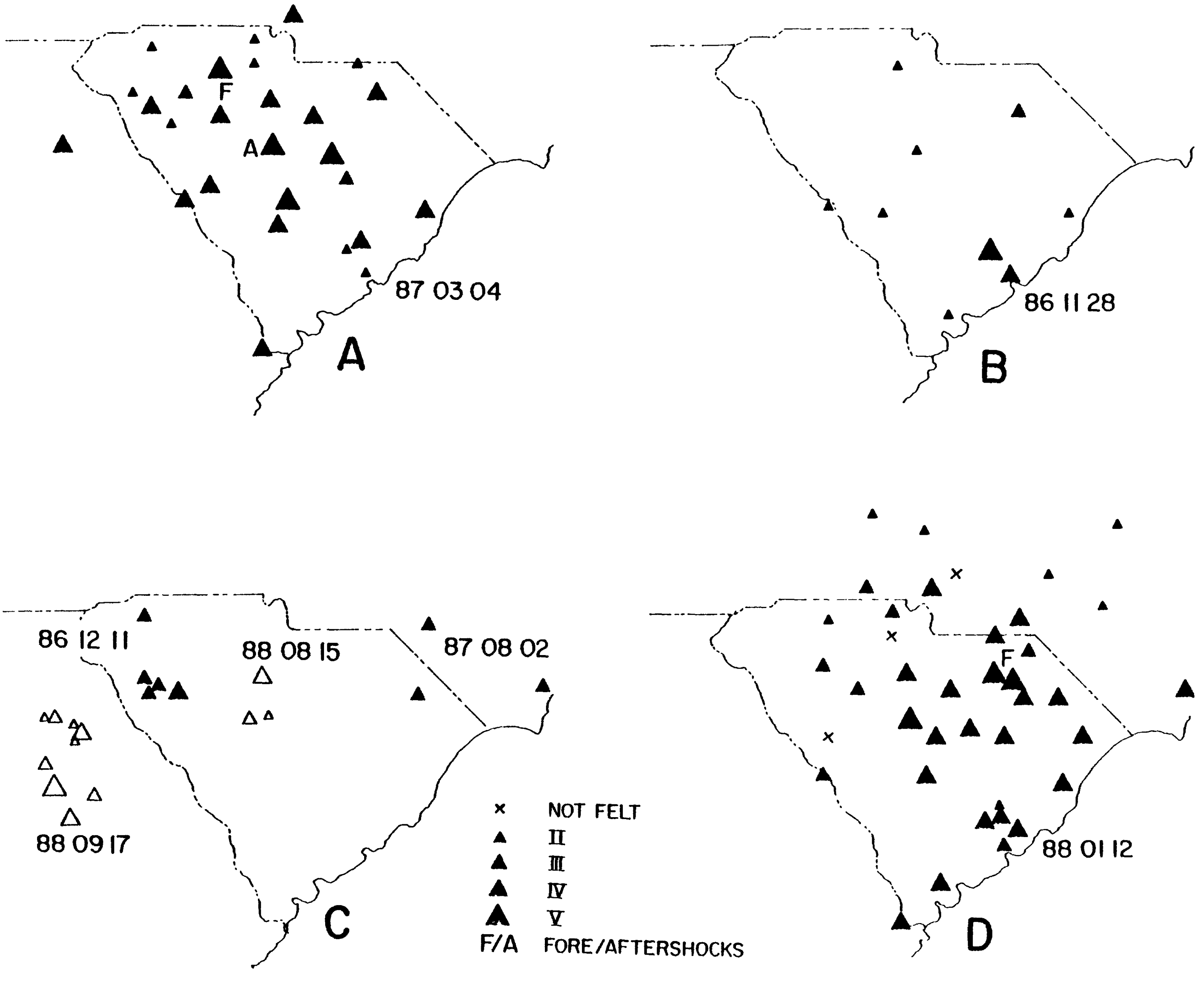

Figure 1.--Seven examples of "aftershocks" of the 1886 earthquake constrained by intensity data from the newspaper search. The earthquakes in A, B, and D are listed in the USGS catalog as originating at the Charleston/Summerville epicenter. The distribution of intensities show that B is probably located there, but A and D are centered far to the north and northwest of Summerville, D is the strongest earthquake in the South Carolina-Georgia seismic zone during 1888-1889. The four earthquakes in C are not in the USGS catalog and they can also be assigned epicenters unquestionably distinct from Charleston/Summerville.

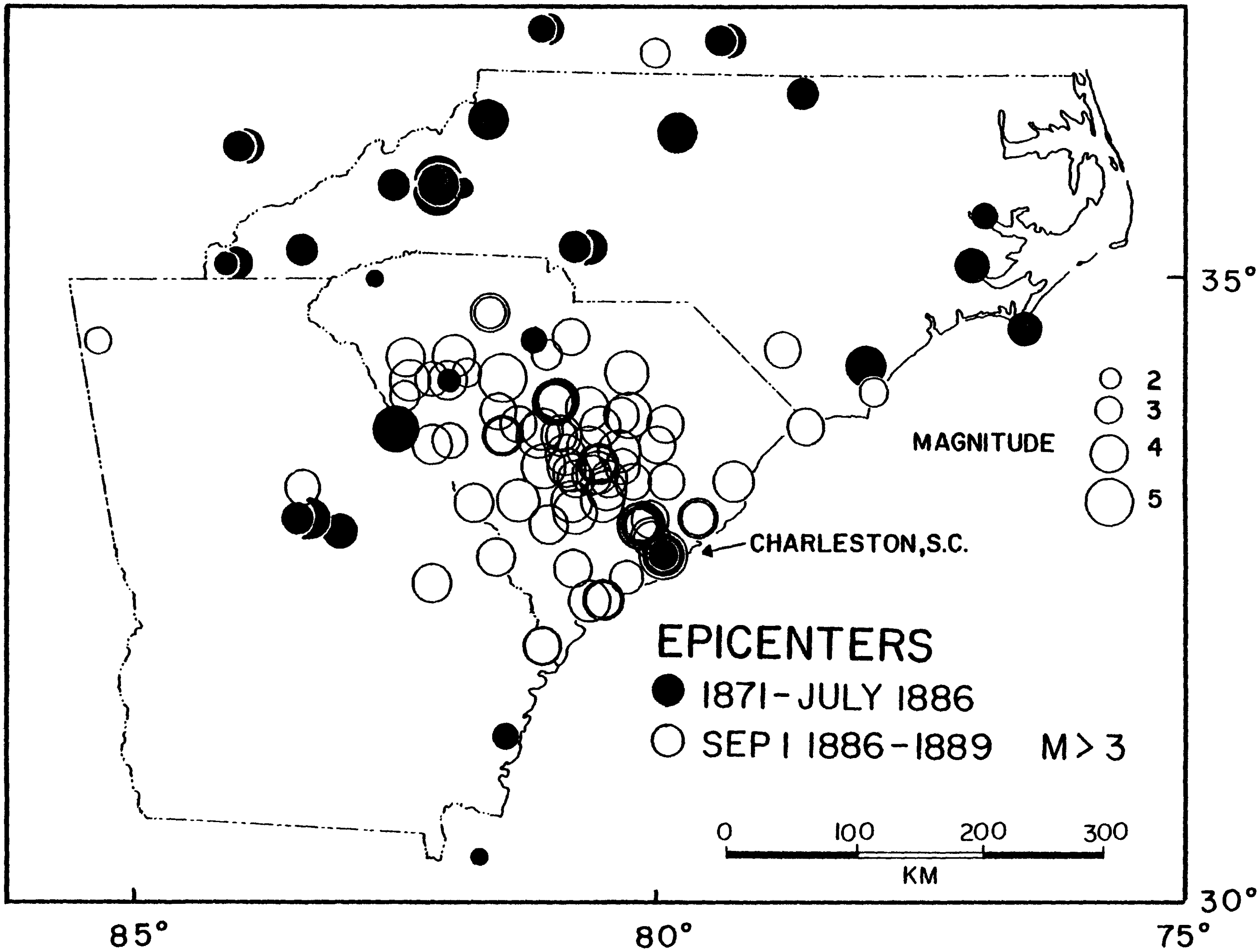

Figure 2.--Epicenters of "aftershocks" of the 1886 earthquake with felt report at more than one town (open circles). Magnitudes are assigned from felt areas. Also plotted are all epicenters from 15 years prior to the main shock (black circles; USGS data with one epicenter eliminated and two added as a result of a partial newspaper search). Our results indicate that a large portion of the South Carolina-Georgia seismic zone became suddenly very active at the time of the main shock. This activity tended to fill the area of low seismicity within a doughnut of relatively high seismicity prior to the main shock. The northeastern and southwestern limits of the "aftershock" zone are better constrained than the southeastern and northwestern limit.

Categories 2 and 3 offer the best epicentral constraints and our conclusions regarding the spatial distribution of seismicity are based primarily on them. In this study we have assigned epicenters at the location of reported maximum intensity, or at the "center of mass" of these locations. Magnitudes have been assigned on the basis of felt area (single town events have been arbitrarily assigned a magnitude based on a felt area of 10 x 10 km). More sophisticated methods could be applied, however they would not alter the results discussed here since they depend on the overall pattern of epicentral locations, rather than on individual epicenters.

The data from the systematic newspaper research provide the first catalog of 1886 aftershocks where earthquake magnitudes and locations are determined from intensity distribution. Following Taber (1914), previous catalogs assume that earthquakes felt in Charleston and/or Summerville during the 1886 aftershock period are located at Dutton's nearby source of the 1886 main shock. Few earthquakes in the catalog are located elsewhere in a vast area including Georgia, South Carolina and North Carolina from 1886 to 1910. From a non-systematic search of archival data, Visvanathan (1980) compiled the only previous catalog of 1886 aftershocks with data on intensity distribution, but he did not use these data to infer new epicenters, excpet for a few (3 in 1886-1889) previously unknown earthquakes with felt reports in South Carolina but not in Summerville or Charleston.

RESULTS

The new data show that the Aug. 31, 1886, South Carolina earthquake coincided with an abrupt increase in seismicity in a large area of the Southeastern U.S., probably over the entire South Carolina-Georgia seismic zone (SCGSZ). This result essentially reverses the picture provided by previous catalogs (Figure 3). Thereafter, the level of seismicity decreased rapidly and in three years it reached what appears to be a much longer-term background level (Figure 4). Previous estimates on the length of the 1886 aftershock sequence vary considerably and tend to be much larger (e.g., Long, 1982).

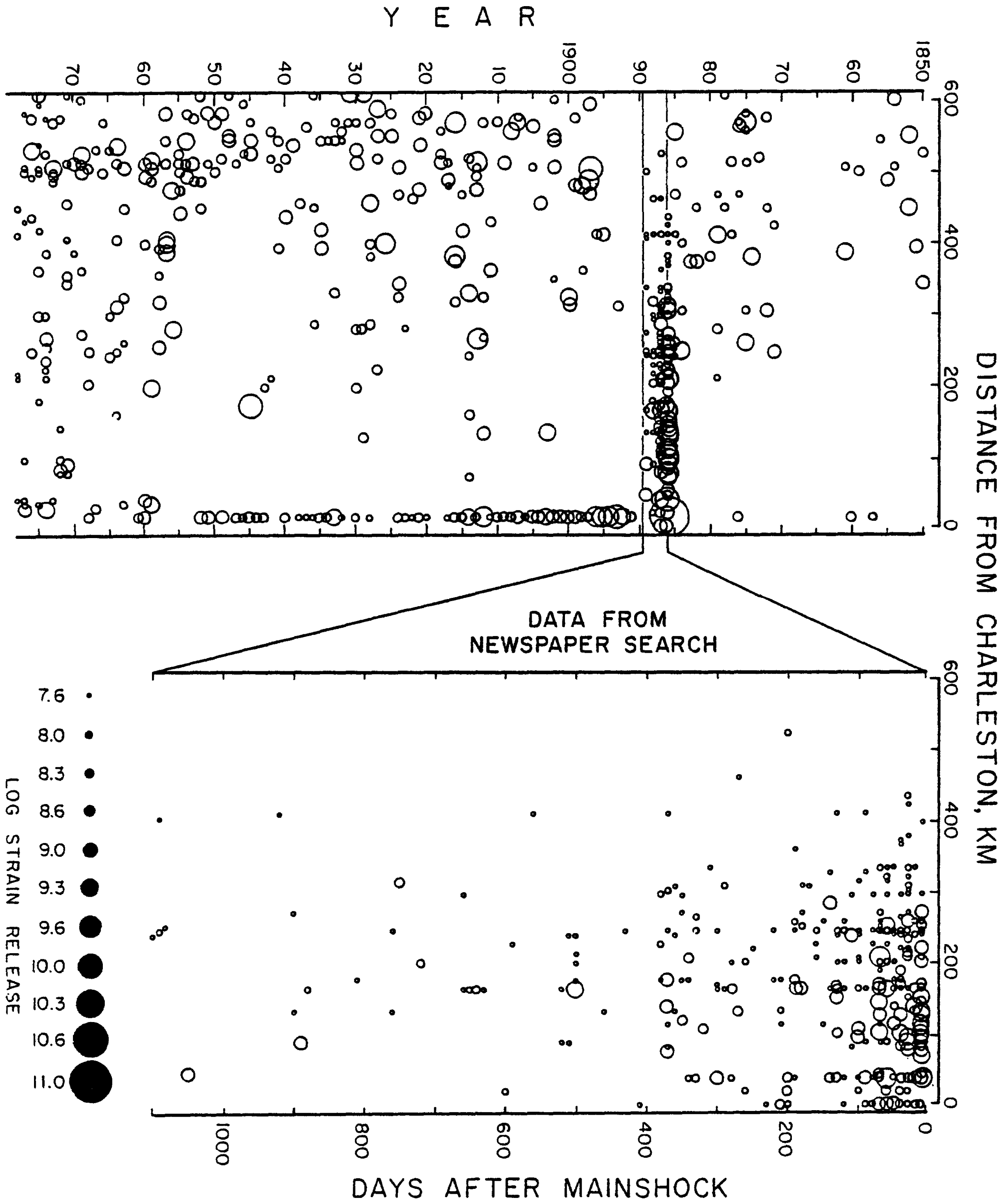

Figure 3.--Space-time plot of seismicity in a circular area of 600 km radius center at Charleston, South Carolina. The data are from the USGS except for the 3 1/3 years following the 1886 main shock (expanded scale) when only data from our newspaper search are shown (≈470 earthquakes). In this same period the USGS lists 135 earthquakes located at the presumed source of the main shock near Charleston/Summerville and none elsewhere in Georgia, South Carolina, and North Carolina. The area covered by the 1886 aftershocks is characterized by relatively low seismicity before the main shock. Note the generally non-radom character of the space-time distribution of seismicity.

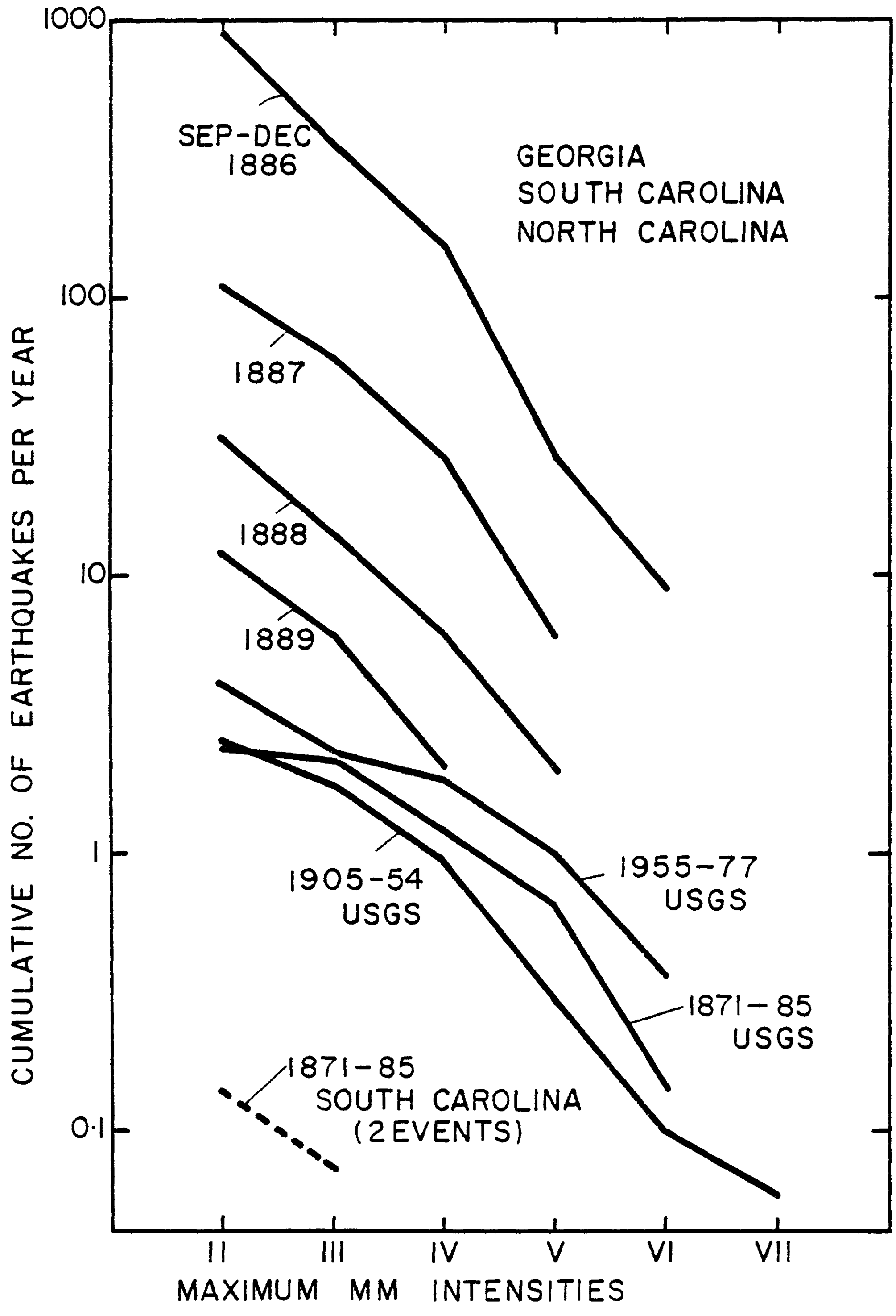

Figure 4. Cumulative distribution of maximum intensitites for earthquakes in Georgia, South Carolina, and North Carolina, before (USGS data) during (our data) and after (USGS data) in the "aftershocks" of the 1886 Charleston earthquake. The number of aftershocks decays logarithmically and by 1889 they seem to reach a longer term level. The distribution and maximum intensities in the aftershcoks are fairly linear (in the logarithmic scale) suggesting that our compilation is relatively complete. The overall level of seismicity in 1889 is similar to the level of seismicity prior to the main shock. But while the "aftershocks" are primarily in South Carolina, most of the earthquakes 15 years prior to the main shock are in Georgia and North Carolina (see Figure 2).

Thus, our results indicate that the time-space distribution of seismicity preceeding and following the 1886 event followed a pattern typical of seismicity associated with large earthquakes. In the ≈15 years prior to the main shock seismicity is relatively high in Georgia and North Carolina, but low in South Carolina (Figures. 2 and 3). We see no reason to suspect a spatial bias in this portion of the catalog which is primarily derived from data compiled by Rockwood from U.S. Weather Bureau reports and from New York newspapers. We have tentatively interpreted this pattern of seismicity as a "doughnut" around the epicentral zone of an impending event. After 15 years of relatively low seismicity in the epicentral area, a few foreshocks occurred within several days of the main shock, but possibly not all of which were located in the Charleston/Summerville area. Then the main shock triggered a burst of seismicity which approximately filled the area within the doughnut.

CONCLUSIONS-RECOMMENDATIONS

At a plate boundary such a pattern of seismicity would probably be associated with a great rupture event where the doughnut and the zone of aftershocks would reflect the size of this rupture. It is not clear to what an extent this analogy is appropriate for an intraplate region. We conclude that the seismicity pattern associated with the 1886 earthquake requires some mechanism, possibly a large tectonic event that could affect the state of stress simultaneously over a large area of the Southeastern U.S., from the Piedmont to the lower coastal plain of South Carolina. The available data, however, cannot distinguish whether a tectonic event which can cause the 1886 burst of seismicity is seismic and coincides with the rupture of the August 31 mainshock, or whether it is primarily aseismic, and both "main shock" and "aftershocks" are in the same family of earthquakes triggered by this aseismic event.

We have proposed that large-scale seismicity patterns can be detected in existing catalogs for the Southeastern U.S. (Seeber et. al., 1982). The most prominent are two bursts of seismicity affecting the entire SCGSZ in 1912-1917 and 1956-1959. Similar coherent changes in the level of seismicity appear to occur within the aftershock sequence at an even shorter time scale (Figure 3). All the earthquakes in these bursts, except possibly the 1886 "mainshock", are small compared to the area affected by these bursts. If real, these seismicity patterns would require relatively rapid coherent changes in stress and/or strength over large areas. Seismicity patterns of this sort at plate boundaries have been ascribed to aseismic slip on the master faults, possibly below the seismogenic zone. It is possible that aseismic slip on some large buried fault is also responsible for the seismicity in the Southeastern U.S. Given the size of the area affected, and the absence of large surface offsets, shallow-dipping to horizontal Paleozoic thrust faults seem the most likely candidates. We have reviewed elsewhere evidence from 1886 coseismic strain effects and other evidence in favor of a back-slip event on reactivated Appalachian detachments or shallow-dipping thrust faults (Seeber and Armbruster, abstract in this volume).

Although a generally accepted interpretation of these large scale coherent changes in the level of seismicity in the Southeastern U.S. is not yet available, they will probably provide an important new constraint on the nature of intraplate tectonics along the Appalachians. In particular, non-random changes in the level of seismicity may provide indirect evidence for major long term changes in the distribution of seismicity so that future large damaging earthquakes may occur where the seismicity is currently low. Efforts should be made to improve the uniformity, and to lower the threshold of completeness in earthquake catalogs. In the pre-instrumental period this can be achieved by a systematic search of newspapers and other archival data. During the instrumental period apparent changes in the level of seismicity can be substantiated against the records of long term stations. The relative level of seismicity in these two periods can be evaluated by calibrating the newspaper coverage during the instrumental period.

The new data from newspapers presented in this paper are from a rather limited pilot project. The results indicate that previous catalogs suffer from uneven and in some cases biased coverage. Previous archival searches in the period we have reexamined have tended to focus on known earthquakes and on data sources from single individuals such as personal diaries. The network of newspapers, if searched systematically, could provide a relatively uniform and complete record of the seismicity over at least half a century prior to instrumental coverage. Our results show that even keeping the effort within practical limitations, a search can be rather complete and final for a given space and time and still require a reasonable effort.

Finally, if the large scale bursts of seismicity in 1886 and later are associated with aseismic slip on major faults, we would expect some surface evidence of the related strain. This evidence may be available in Cenozoic faulting and, possibly, in periodic geodetic measurements. Cenozoic fault displacements seem to be rare within the Coastal Plain, but they have been documented along the Fall Line (e.g., Belair fault, Stafford fault system). Documentation on Cenozoic faults, however, is poor in the Piedmont, Blue Ridge and folded Appalachians, perhaps because stratigraphic age control is generally not available. We recommend a systematic search of Cenozoic fault displacements in these provinces, particularly near the southeast facing topographic front of the Blue Ridge which, according to some, may be fault controlled (e.g., Hack, 1979).

Geodetic data seem to suggest high rates of movement almost everywhere along the Appalachians. There are certainly problems with some but not necessarily with all of the data. For example, high rates of vertical differential movement in coastal Maine are substantiated by several lines of evidence (Borns, et. al., 1983). A program should be started whereby selected sites along the Appalachians are closely monitored for deformation and/or tilt, in a program akin to the program of quasi continuous geodetic control currently active along the San Andreas fault system.

REVERSE FAULTING AS THE SOURCE OF EARTHQUAKES ALONG THE EASTERN SEABOARD OF THE UNITED STATES: PROBLEMS AND NEEDED RESEARCH

by

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INTRODUCTION

The principal style of faulting evident along the eastern seaboard that postdates the early Mesozoic opening of the Atlantic Ocean is reverse faulting. The faults strike generally northeastward and, although active through at least most of the past 100 m.y., have developed only very small cumulative displacements in Cretaceous and Cenozoic strata. The existence of these reverse faults has led to the hypothesis that movement on such faults is responsible for much of the seismicity along the eastern seaboard (Wentworth and Mergner-Keefer, 1981, 1983). The hypothesis builds from the geologic premise that ongoing deformation should be expressed in the rock record and leads to the inference that the eastern seaboard should experience occasional damaging earthquakes as large as about magnitude 7, the latest of which was the 1886 Charleston event.

Although consistent with most available evidence, the hypothesis extends well beyond the facts in hand and conflicts with the compression direction determined from recent earthquakes at Charleston. Further work is required to resolve that conflict, to test and improve the foundation and details of the argument, and to determine its relation to alternative explanations of east-coast seismicity. No single definitive experiment is available; efficient progress will require a well planned and coordinated interdisciplinary effort.

Pursuit of evidence bearing on the reverse fault hypothesis should be coordinated with work on other possible explanations of east-coast seismicity. Throughout, the work should involve three general lines of inquiry that, together, will provide the most powerful approach to the problem.

1) Characterize the most recent tectonic regime represented in the geologic record and project its behavior forward in time to predict present tectonic behavior.

2) Examine present tectonic behavior directly through studies of earthquakes, in-situ stress, and geodesy.

3) Make sense of both through an understanding of causes.

Only a small number of selected references are cited in this paper. Wentworth and Mergner-Keefer (1981, 1983) should be consulted for more thorough documentation.

THE REVERSE-FAULT HYPOTHESIS

The hypothesis argues that an Atlantic Coast domain undergoing northwest-southeast compression extends from Georgia into Canada between the Appalachian Highland and the eastern edge of the continent. This compressive regime has been driving reverse faults at low and declining rates for at least the past 100 m.y. and possibly since soon after Atlantic rifting. The reverse faults are presumed to be scattered throughout the domain and to have developed largely along parts of pre-existing structures, particularly zones of early Mesozoic normal faulting. The few well-documented reverse faults offset the base of Cretaceous strata about 100 m or less and show movement rates of about 0.3 m/m.y. over the past 50 m.y., assuming movement to the present. The youngest documented offsets involve probable Pliocene and-or Pleistocene surficial deposits. The available earthquake record, particularly near the early Mesozoic Ramapo fault west of New York City and in eastern New England, shows largely north- to northeast-striking reverse mechanisms; these are consistent with a continuation of the reverse faulting into the present. Focal mechanisms from recent earthquakes in the 1886 Charleston meizoseismal area are different, but northeast-trending reverse faults with progressive Cretaceous-Cenozoic offset do occur there. Under the assumption that northeast-trending reverse faulting caused the 1886 earthquake, the frequency of such large earthquakes (taken as magnitude 7) throughout the 2000-km-long domain can be estimated from fault offset rates and other geologic evidence and assumptions. This estimate and one derived independently from the historic seismic record yield the same value, on the order of one per thousand years.

PROBLEMS AND FURTHER RESEARCH

Testing of the reverse-fault hypothesis involves three principal topics: the origin and history of the reverse-fault domain, its persistence into present time, and its relation to the 1886 Charleston earthquake. The most direct test is comparison of the relation between reverse faults and the source geometries of earthquakes. To this end, regional seismic networks should be maintained and the more active areas should be studied in sufficient detail to obtain good focal mechanism solutions. Progress will depend on the slow natural occurrence of earthquakes; so far, except for the Charleston area itself, results of such monitoring are largely consistent with the reverse-fault hypothesis.

History of the Reverse-Fault Domain

The very limited inventory of well-documented reverse faults (Prowell, 1983), although growing, must be systematically enlarged. Because a thorough study of all possible reverse faults in the domain is a practical impossibility, an estimation procedure based on present knowledge and study of selected additional sites or traverses is needed. A program should be designed to address three issues: the distribution of reverse faults in the domain, their movement histories, and their relation to early Mesozoic faults and other identifiable structures. To succeed, it must attend to the practical differences throughout the domain in geologic record, appropriate investigative techniques, confidence of results, and present level of knowledge. It will be important to distinguish any major differences in behavior from place to place within the domain and to explicitly address the suggestion that dip slip may be subordinate to strike slip on these faults.

In the Coastal Plain and offshore, the most rapid and definitive progress will require properly designed reflection profiling to search for and document faults. Because confident identification of stratigraphic horizons is essential to determine fault histories, selected drilling, surface geology, and supporting biostratigraphic work will also be required.

In the Piedmont the principal approach must be geomorphic. Consideration of stream profiles, topographic relief, and rock resistance, for example, have recently led Hack (1982) to conclude that parts of the Piedmont and Appalachian Highland have undergone late geologic warping and faulting. Mayer and Wentworth (1983) have successfully distinguished the up-and downthrown sides of the Stafford fault zone and its southwestward projection in the Piedmont using statistical analysis of various measures of the shape of small drainage basins. The somewhat analogous Sierran foothills of California (Wentworth and Mergner-Keefer, 1983), in which some stratigraphic control on Cenozoic faulting is still preserved, may offer a useful laboratory for development and testing of techniques. Where young deformation in the Piedmont is suggested by such approaches, soil, saprolite, and colluvial-alluvial sequences, deliberately exposed by trenching, should also be studied to better determine the pattern and history of deformation.

It is not clear what drives this compressive system along the continental margin. Some relation to Atlantic spreading and the age of adjacent oceanic crust is suggested by the declining rate of fault offset and the orientation of the domain and its faults perpendicular to the age gradient of the adjacent oceanic crust.

Quaternary and Present Behavior

The long duration of the northwest-southeast compressional regime and the apparent decrease in rate of reverse faulting through time make it important to test explicitly whether the reverse faulting has persisted to the present. Changes in deformation rate or style or even a significant change in tectonic regime are possibilities to consider. Although Atlantic spreading has been generally consistent for nearly 200 m.y., it has not been constant. The latest shift in plate behavior in the Atlantic, a modest change in spreading direction and a near doubling of the half spreading rate to the west, occurred about 1.7 m.y. ago (McDonald, 1977, and K. L. Klitgord, oral commun., 1983). There are also suggestions of a change in style or rate of deformation elsewhere near the beginning of the Quaternary from such widely separated places as New Zealand, Japan, California, and the Alps.

The little available evidence of Pliocene and/or Quaternary offsets in the Atlantic Coast domain does support continued reverse faulting. Unfortunately, in contrast to the western United States, rates of fault movement in the east are so low that it is difficult to resolve evidence of faulting from the Quaternary record. The tendency for basement offsets to decay upward into open folding through thick sedimentary cover exacerbates this problem. Regardless, favorable sites for identification of Quaternary stratigraphy and recognition of young faulting should be sought along the traces of mapped or suspected faults and these should be carefully explored by mapping, drilling, and trenching. It is important to determine the recency of faulting at the various places where Cretaceous-Cenozoic faulting is already recognized. In this regard the faults in the meizoseismal area of the 1886 earthquake that have been identified in the lower Coastal Plain section by reflection profiling should be traced to the surface using high resolution profiling, drilling, and trenching.

The most important test of continuity of the reverse-fault regime into the present comes from measures of modern stress and strain, particularly the earthquakes themselves. Available evidence from earthquakes along the Ramapo fault and in the northeast does indicate reverse faulting, but much more data are needed. It may be worthwhile to establish or extend local networks to cover selected reverse faults, such as the Stafford zone in Virginia. Continued, probably expanded, seismic monitoring and determination of good locations and focal mechanism solutions, if properly organized, is the single most important element of needed research.

The possibility that slip rates of the reverse faults have increased in the Quaternary must be entertained, although the first effort to compare the frequency of large earthquakes from historic seismicity and longer term geologic evidence in the context of the reverse-fault hypothesis suggests consistency through the past 50 m.y. (Wentworth and Mergner-Keefer, 1981). Such an increase may be required by postulates of return times as short as a few thousand years for large earthquakes from single sources. The reverse-fault hypothesis, as presently conceived, leads to return times closer to a million years (Wentworth and Mergner-Keefer, 1981). It is also possible that the rate of deformation varies through time and that relatively short bursts of activity move from place to place and are balanced by long periods of quiescence. Resolution of such behavior will require detailed fault histories.

Relation to the 1886 Charleston Earthquake

The extensive recent investigation of the setting of the 1886 Charleston earthquake demonstrates excellent geologic compatibility of that setting with the reverse fault hypothesis. The meizoseismal area of the 1886 earthquake lies at the northeast-striking border of an early Mesozoic redbed basin where northwest-dipping normal faults should occur. Associated with this border in the overlying section are northwest-dipping, northeast-striking reverse faults of modest displacement that progressively displace Cretaceous and lower Tertiary strata. Relief on unconformities and an incomplete late Cenozoic section obscure any evidence of younger offsets.

Small recent earthquakes, however, don't seem compatible with the northwest-southeast compression characteristic of the Atlantic Coast domain. Compression axes determined from earthquakes in the 1886 meizoseismal zone and 185 miles to the northwest at Monticello Reservoir in the Piedmont have a northeast trend (Talwani, 1982; Talwani and others, 1980). These results pose a serious problem, because northeast-striking faults cannot be driven by northeast-striking compression and available evidence indicates that the Ramapo, Stafford, and Belair fault zones, in particular, are largely reverse with only slight strike-slip components.

Two possible resolutions of this conflict should be tested.

1) Such a local departure of the compression direction from the relatively consistent pattern found elsewhere along the eastern

seaboard raises the possibility that the Charleston results are in error, perhaps due to uncertainties in the seismic data or their interpretation. Results for Monticello Reservoir might then be dismissed because the events there are so shallow (less than 2 km). The possibility of such error should be tested by careful review of the character and quality of the seismic data and of their interpretation. Continued monitoring of earthquakes should provide further data to test the pattern.

2) The northeast compression direction could indicate a recent shift in direction from that responsible for the northeast-striking reverse faults. This is not true in the northeast, for earthquakes there do not indicate such a shift, as already noted. It also seems unsatisfactory to postulate such a shift only in the Charleston-Monticello area, for stress patterns as presently known throughout the United States are striking in their broad regional consistency. Any such shift would more likely involve much of the southwestern part of the Atlantic Coast domain, a region in which earthquake focal mechanisms are scarce. This possibility should be tested by gathering additional earthquake and other data and by reviewing existing data, including that for the 1976 Trenton earthquake near the Fall Line south of Monticello Reservoir. A preliminary focal mechanism for that event showed northeast-striking reverse movement (Talwani, 1977). Such a possible shift in compression direction emphasizes the need to better understand the driving forces for northwest-southeast compression across the eastern seaboard. One test of a change in direction is to find evidence for a change in the driving forces that has affected only the southwest part of the Atlantic seaboard.

Other Considerations

The late Cenozoic behavior of the Appalachian Highland and its implications for earthquake generation need exploration. It is clear that late geologic uplift of the range has occurred (Hack, 1982), and its eastern front may well have resulted from faulting of considerably larger magnitude than that recorded within the Atlantic Coast domain. As in the Piedmont, the principal geologic approach must be geomorphic, although uplift rates inferred from apatite fission-track ages may be helpful.

It has been proposed that the 1886 Charleston earthquake was generated by or was otherwise related to recent movement on a deep Paleozoic decollement fault. Listric faulting in the Paleozoic or Early Mesozoic could provide a geometric link between such recent thrusting and movement of overlying reverse faults. The reverse-fault hypothesis does not depend on movement of an underlying decollement fault, but it can accommodate it. The key questions relate to the validity of the decollement hypothesis itself. There is no recognized geologic evidence of Cretaceous-Cenozoic thrust movement, such as tear faults or progressive tilting of blocks, and the driving forces for such a system are at least as obscure as for the compression that produced the reverse faults. If the gravitational potential of the high topography of the Appalachian Highland is called on to drive the thrust, then the implied lowering and extension must be reconciled with the geologic uplift required there by geomorphology. Although some of the Early Mesozoic normal faults may be listric, the fact that mantle-derived magma was extruded during that period implies fault penetration deep into the crust. This suggests that at least some of the normal faults offset the Paleozoic thrusts, rather than flattening and joining them. On the positive side, if movement of a thrust plate were involved in recent east-coast tectonics, distortion within the plate might account for more local shifts in compression direction through time than would otherwise be expected.

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DID MOVEMENT ON A NORTHEAST TRENDING LISTRIC FAULT NEAR THE SOUTHEAST EDGE OF THE JEDBURG TRIASSIC-JURASSIC (?) BASIN CAUSE THE CHARLESTON, SOUTH CAROLINA, 1886 EARTHQUAKE?

by

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RESULTS OF GEOPHYSICAL AND GEOLOGICAL RESEARCH

Results of a decade of geophysical and geological research by the U.S. Geological Survey on the cause of the Charleston 1886 earthquake, although not providing a definitive determination of its source, have allowed the construction of a hypothesis which contains elements of several earlier ideas. The apparently numerous hypotheses discussed in the last several years are beginning to converge.

Multichannel seismic reflection profiles on land and offshore have defined a very smooth reflector extending over an area at least 100,000 km^2 correlated with a 0.8 km deep Jurassic age basalt layer (the Pre-Cretaceous unconformity) where penetrated by a core hole in the meizoseismal zone of the 1886 earthquake. The reflection from the basalt indicates a regional southeast dip of about 0.3, for the layer, steepening an order of magnitude over the faults described below. If the Charleston area had a high recurrence rate for earthquakes of similar magnitude (6.5-7.0) to that estimated for the 1886 event, one might expect a very disrupted and highly faulted surface on the basalt. Instead there is only the northeast trending Summerville flexure (slightly dipping to the southeast) in the meizoseismal area. Within this flexure, northeast trending, northwest dipping high angle reverse faults (the Cook and Gants faults) warping the basalt surface and Upper Cretaceous and Cenozoic Coastal Plain sedimentary rocks, have been reactivated from an older normal fault (or faults) associated with the southeast edge of the Jedburg Triassic-Jurassic(?) basin. The small displacement (50 m) reverse faults active from Late Cretaceous or earlier time have moved progressively through

Cenozoic time to at least as recently as Miocene time; possibly they have been active to the present and have a causal relation to seismicity. The length of the Summerville flexure and the Cooke and Gants faults are sufficient to account for the magnitude of the 1886 earthquake.

Epicenters in the 1886 meizoseismal area, determined from about forty earthquakes since 1973, using data obtained by the South Carolina seismic network cluster over the Summerville flexure near the Cooke and Gants faults along the southeast boundary of the Jedburg basin. Relocated epicenters of pre-1973 instrumentally recorded earthquakes also cluster in this zone. Some have considered all of these earthquakes as aftershocks of the 1886 event. Seismicity in this region in the past few decades (after the decay of most aftershocks) is not higher than at a number of other places in the Eastern United States, and had there not been a large historical earthquake, one would not identify the Charleston-Summerville area as different from these other similar areas in terms of seismic risk. Hypocenters determined from the seismic network indicate depths ranging from 3-13 km with an uncertainty of about 2 km. These depths are greater than that of the Jedburg basin, and no direct causal relation between the basin and seismicity is implied. The basin bounding faults would, of course, be expected to extend deeper than the sediment fill. Several composite focal mechanism solutions have been constructed using P-wave first motion data from about a dozen of these earthquakes but because of their sparcity, and polarity uncertainites the results are ambiguous. A single event (November 22, 1974) however, indicates a northwest trending reverse fault moving under northeast-southwest compression which is in right angles to the basin boundaries reverse fault observed.

Deep multichannel seismic reflection profiles on land and offshore in the Charleston area have defined a surface at about 11.4 ± 1.7 km depth which has been interpreted as a decollement extending over an area of at least 30,000 km^2 but probably not a simple continuation of the Appalachian decollement to the northwest. Possibly the high angle northeast trending reverse faults in the Summerville flexure near the southeast boundary of the Jedburg basin flatten at depth in a listric sense onto the decollement but neither the seismic reflection data nor the calculated hypocenters have been sufficient to define such a listric fault. Within uncertainty limits in the depths it is possible to state with some confidence that all hypocenters are at the same depth or shallower than the decollement. Listric faults, such as suggested here, have been identified on seismic reflection profiles over the Riddlevill basin in Georgia and Virginia. A suggestion of listric faulting can be seen in the profile across the northwest houndary of the Branchville basin on its northwest side.

The meizoseismal area of the Charleston 1886 earthquake, and the Gants, Cooke and Drayton faults near the southeast boundary of the Jedburg basin and other high angle, northeast trending, Cenozoic reverse faults, such as the Helena Banks fault offshore and the unnamed fault marking the northwest edge of the Branchville basin near the Bowman cluster of epicenters, all lie within a well defined low magnetic gradient area called variously the "Charleston terrane", "Charleston block" or "Brunswick terrane". The Charleston terrane extends offshore beneath the continental shelf. Within this terrane in South Carolina and Georgia three Triassic-Jurassic(?) basins have been identified using seismic reflection profiles. Several other Cenozoic high angle reverse faults (e.g. the Helena Banks fault offshore) have been identified on the seismic reflection profiles.

The terrane of low magnetic gradient as well as the surrounding region lie within the regional horizontal compressive stress field of eastern North America. The best determination of maximum horizontal compressive stress direction in this area is northwest-southeast as attested to by Cenozoic reverse faults having northeast trends that have been reported here and in other locations in southeast North America. Some of these faults from Virginia to Georgia have been active within the last million years which indicates there has been no dramatic change in stress direction since Tertiary time.

Based on the results and inferences summarized above, I suggest the following hypothesis: the Charleston 1886 earthquake may have been caused by movement in the regional, (northwest-southeast-directed compressive stress field) on a reactivated older fault zone associated with the faults interpreted near the southeast edge of the Jedburg Triassic-Jurassic(?) basin, which may flatten as listric faults onto a decollement. The actual fault movement responsible for the 1886 earthquake could have been along either steeply dipping or subhorizontal surfaces but its location in relation to the decollement was influenced by the presence of (intersection with ?) the highangle faults. Most speculative is the cause of the decollement but conventional wisdom has its origin as an overthrust fault at the closing of the lapetus in Paleozoic time. In Triassic and early Jurassic time, the rifting and localization of basins occurred in what is now the low magnetic gradient Charleston terrane in continental transitional crust. The presence of the Helena Banks high angle reverse fault offshore, not associated with a basin, suggests that the basin-bounding faults are only particular zones of weakness that moved in a normal sense allowing basin filling during Triassic-Jurassic rifting, but that other probably pre-existing zones of weakness, which might have been present, did not move appreciably at that time. Subsequent to stress reversal from regional extension to compression, possibly as early as Jurassic time, the high angle faults were reactivated in a reverse sense. Presumably there was compressional movement on the decollement and flattened parts of the listric faults as well.

SUGGESTED STUDIES TO EVALUATE THE HYPOTHESIS

This hypothesis can be tested in several ways. If multichannel seismic reflection profiles across either the reverse faults bounding the Jedburg basin in the meizoseismal area of the 1886 earthquake (and recent seismicity) or the possible listric faults observed bounding the Branchville basin near the Bowman epicenters could better define these reactivated boundary faults and demonstrate whether or not they flattened into listric faults splaying onto a decollement, it would go a long way toward evaluating the proposed idea. Therefore seismic profiles, of sufficient quality and long enough recording time to obtain the expected reflections should be measured across the boundaries of both basins. This is a difficult experiment both geophysically and operationally (the later because of high population density in the Jedburg basin area). Possibly the profiles over the Jedburg basin could be more easily measured northeast and southwest of the populated area assuming the basin and bounding faults extend sufficiently far.

A second critical experiment is the determination of the geometry and sense of movement on faults presently active in the area using, preferably three component, seismographs at quiet sites or in boreholes. Magnitude-frequency observations from existing data in the area suggest about an order of magnitude more earthquakes could be observed in a given time if an order lower magnitude earthquake could be measured. Focal mechanisms determined using the full wave form rather than only first motion of P-wave arrivals would obviate some of the difficulties with the previous data set.

A third type of study needed is a reevaluation of old and recent geodetic triangulation data to evaluate sense and magnitude of strain either before and after the 1886 earthquake or during any time interval the data might allow. The results of this relatively inexpensive study, if possible to obtain, would be very useful in independently evaluating the regional stress field present which produces earthquakes.

Implicit in this report is the assumption that the capability of structures and other conditions in the Charleston area to produce a major earthquake is not unique to that region. If this is the case, evidence of faulting during Cenozoic and possibly recent time should be available eslewhere. Although various ongoing studies are attacking this problem on land, the available evidence in the marine evnironment has not been looked at sufficiently. Over 30,000 km of multichannel reflection profiles collected by USGS over the Atlantic continental margin since 1973 have been studied as part of a geologic framework investigations. These data have not, however, been examined carefully for evidence of small displacement faults beneath the continental shelf other than incidentally to the main objective of that work. Despite this, several faults similar to those near Charleston have been found. Some reprocessing would be required but the small cost compared to the initial investment in collection is easily justified. If there were a pattern (or absence) of Neogene high angle reverse faults offshore along the U.S. Atlantic seaboard it would have a direct bearing on the evaluation of possible seismic risk.

Additional field geologic studies are required to possibly evaluate recurrence intervals at Charleston from evidence that might be present of sand blows and other geomorphic and surficial geologic phenomena associated with large earthquakes. The techniques and reliabilty of this approach has only been demonstrated elsewhere within the last decade and availability of experienced researchers in this area would allow such studies in the meizoseismal area of the 1886 earthquake.

THE CHARLESTON, SOUTH CAROLINA, SEISMOGENIC ZONE: TERRANE DECOUPLING AND HORIZONTAL VERSUS VERTICAL SOURCE GEOMETRY

by

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CHARLESTON-TYPE SOURCE STRUCTURE

We interpret the available geological, geophysical, and seismological evidence as defining two candidates for the sources of the Charleston seismogenic zone (CSZ), i.e., faults with either horizontal or vertical orientations. Both candidates have received support recently. The Virginia Tech geology-reflection seismology-seismicity results in central Virginia suggest that a detachment fault and associated listric splay faults are being reactivated in that locale. The detachment there lies at depths of some 8-10 km and exemplifies the horizontal source models proposed for Charleston by some USGS and Columbia University researchers. Conversely, the models of steep and perhaps intersecting faults for the CSZ, as proposed recently by investigators at the USGS and the University of South Carolina, define vertical source geometries.

Finally, offshore-onshore, northwest-trending cross structures have also been postulated by other Columbia University investigators as being seismogenic at Charleston, but we do not consider that as likely as the other two models.

The following discussion considers, in turn, aspects of each of the above seismogenic structural types.

1) Horizontal source zone

There is a question as to whether the Appalachian detachment extends far enough southeastward to reach the Charleston locale or if other, smaller detachments occur in the locale. Also unresolved is whether the earthquake focal depths are above (seismicity in overthrust suspect terrane) or below (seismicity in the underlying cratonic or suspect basement) the hypothesized detachment, or on it. Thus, we do not yet have an adequate understanding of the details of the seismogenic structure and its relationship to the host area's structure.

The following investigations could test the hypothesis of a horizontal source zone:

a) Joint-Hypocenter-Determination (JHD) and velocity model studies of the diffuse Piedmont seismicity in South Carolina and northeastern Georgia to test if there is a general shallowing of the foci northwestward. Is the seismic activity predominately above or below the postulated (or known) detachment depths?

b) If the Charleston source is due to back slip over a portion of the Appalachian detachment, then somewhere updip, in the Piedmont in SC or in the Valley and Ridge/Blue Ridge provinces at the TN/NC border area, there should be normal faulting. Use should be made of the above JHD results to develop composite focal mechanism solutions (CFMS) for the South Carolina Piedmont that utilize P-wave polarities, $(SV/P)_z$ ratios and, if possible, spectral and waveform analysis. Such a study for the TN/NC border region has been initiated recently as a cooperative effort between the Seismological Observatory at Virginia Tech and the Tennessee Earthquake Information Center of Memphis State University.

2) Vertical source

Most of the recent Charleston area epicenters fall into a cluster and two recent attempts to subdivide that cluster have produced conflicting results (Tarr and others, Seism. Soc. Am. Bull., 1981; Talwani, Geology, 1982), although both studies report steeply dipping nodal planes. The special relocation efforts by Talwani add credence to his inference of intersecting faults that strike NW with high angle reverse movement and strike NNE with right-lateral strike-slip motion. However, that interpretation requires the following additional support: a) specification of horizontal and vertical uncertainties associated with all the hypocenters (a relative focal depth accuracy (1 km) has been cited only for a sequence of four seismic events on October 30, 1978; blast epicenters were also cited as being located within 1 km; behavior of calculated depths for blast were not described), b) demonstration that the uncertainties in the hypocentral parameters are small enough so that the results are clearly inconsistent with a horizontal source, and c) specification of the adequacy of the CFMS by showing plots of the distribution of the observed P-wave polarities employed to determene those CFMS (the sloutions were cited as well-constrained with orientations probably accurate to ±10,). Also, the CFMS need to be corroborated by $(SV/P)_z$ amplitude ratios and again, if possible, spectral and waveform studies. Finally, we note that 40% (10 km) of the length (25 km) of the main NNE-striking zone (D in Talwani, 1982) is due to extension out to a single, outlying epicenter. That single event is nearly as close (11 km) to three Adams Run events to the SSW that were not included in the NNE-striking zone.

3) Offshore-onshore cross structures

The growth of offshore fracture zones in the Atlantic Ocean, after nucleation at old, weak zones onshore, has been hypothesized to explain the two transverse seismic zones in the Southeastern United States (central Virginia and South Carolina-Georgia zones) by Sykes (Rev. Geophys. Space Phys., 1978) and Nishenko and Sykes (Am. Geophys.

Un. Trans., abs., 1979). The principal difficulties that we see with this model for Charleston are: 1) There is no known offshore seismicity on the Blake Spur fracture zone. That absence has now been confirmed to relatively low magnitude levels by several years of network monitoring. 2) If a preexisting weak zone, transverse to the Coastal Plain and the Appalachians, was reactivated to nucleate the Blake Spur fracture zone, that weak zone must predate Atlantic rifting. Then a hypothesized extension of that weak zone across the suspect terranes would be unlikely considering the probable complexities of terranal accretion and the associated strike-slip movements (Kent and Opdyke, Jour. Geophys. Res., 1978; LeFort and Van der Voo, Jour. Geol., 1981) likely to have accompanied such accretion. Further discussion of this topic is in the paper by Wheeler (this volume).

DECOUPLING OF THE CHARLESTON HOST TERRANE?

The CSZ is contained within the "Charleston block" of Popenoe and Zietz (USGS Prof. Paper 1028, 1977), or the roughly equivalent Brunswick suspect terrane (BST) of Williams and Hatcher (Geology, 1982). The identification of the block or terrane is based on regional variations in the patterns of potential field anomalies. That identification is also generally consistent with variations in the spatial distribution of seismicity as mapped by a seismic network (a tendency toward "clustering" within the terrane and toward a more "diffuse" pattern outside of the terrane to the northwest) and by the fact that the CSZ is the only portion of the Atlantic Coastal Plain with appreciable seismicity.

The above factors raise the question of whether the Brunswick suspect terrane (BST) is mechanically decoupled from the adjoining Avalon suspect terrane (AST) on the northwest. The answer is important because if the boundary is uncoupled, then the combination of stress field and structural fabric that produced the Charleston earthquake within the BST may not occur outside the BST. What is known of the inferred BST-AST boundary, as it is presently defined, is that it appears to be seismically inactive (there is no superposed linear concentration of epicenters) and seems to lack a distinct potential field pattern (there are no superposed linear concentrations of gravity or magnetic anomalies at the scales of available maps). Note, however, that such linear expressions would not be developed if there should be a shallow dip to the contact or if the contact has an appreciable horizontal dimension.

It appears to us that seismic strain-release may be occurring primarily within the individual terranes (BST and AST) and not at the terrane boundaries. Whether this is due to different structures, different stress regimes, or both in the individual terranes is unknown. If there is strong coupling between adjacent terranes, then the contemporary stress field should be relatively uniform across their boundary. Differing structures would be required to account for differing seismicity characteristics. However, if there is little or no coupling, the transfer of the regional stress from one terrane to its neighbor would not be uniform. In principle, then, as previously mentioned, different seismicity patterns could result from those different stresses acting on similar types of structures.

We have virtually no information on the nature of terrane boundaries in the critical third dimension of depth. For example, we do not know the spatial distribution of cratonic and terrane basement beneath thrust sheets or the location and nature of the rooting of those sheets. Also, the terrane names and inferred boundaries of Williams and Hatcher are likely to change with additional information.

PROPOSED INVESTIGATIONS

Reflection seismic profiling is needed that extends from the Piedmont in northwestern South Carolina, across the BST-AST boundary and on into the BST and the Charleston area. It is, however, essential that such profiling be accompanied by bedrock geologic mapping, field and laboratory measurements of reflectivity (acoustic impedance contrasts) and potential field modeling along the profile routes. Only such intensive, focused applications are likely to characterize clearly the boundary and nature of the BST-AST coupling.

FAULT REACTIVATION MODELS FOR THE ORIGIN OF EASTERN UNITED STATES SEISMICITY: DOES THE SOLUTION TO CHARLESTON RESIDE AT CHARLESTON?

by

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INTRODUCTION

Programs to study Eastern United States seismicity should have as their cornerstone the goal of explaining the geologic causes of the historic and instrumental seismic record. At the present time the ruling hypothesis is that geologic structures much older than the current stress field are being reactivated to produce seismicity. However, certain examples of new breaks serving as seismic sources have been proposed (New Brunswick and Blue Mountain Lake). Geologic features identified at New Madrid, the Central Virginia Seismic Zone, Ramapo, and inferred to be present at Giles County Virginia, and at Charleston, South Carolina, for example, are cited in support of the reactivation hypothesis. it is clear that certain tectonic models utilizing the reactivation concept can be proposed and tested against the existing (or to be collected) instrumental data. Focused studies that utilize a high-quality instrumental data base, well-thought-out geologic structural models, and apply constraints from knowledge of the subsurface configuration of potential fault surfaces from seismic reflection, refraction, and other geophysical methods hold the greatest potential for deciphering seismic source zones in the Eastern United States

MAJOR DEFICIENCIES EXIST IN MOST APPROACHES TO THE PROBLEM; TESTABLE MODELS ARE REQUIRED

Geologic seismologic research in the Eastern United States that seeks to explain the causes of seismicity needs to be able to identify present day seismogenic structures. Study of three types of target areas have been undertaken in the East:

1) Search for the cause of the elusive pre-instrumental, big bang (Charleston)

2) detailed studies in areas of micronetworks (Moodus, Conn.)

3) geologic study of technologically active or suspiciously active areas (Adirondacks, Coastal Maine)

Each of these approaches is valid, but target areas usually suffer from major gaps in the amount of pertinent data that are obtainable.

If a model to explain the cause of present day seismicity is desired, then target areas must contain enough of the requisite data base to allow development of hypotheses independently arrived at for that area. These hypothesis need not be unique to the target area but should be testable by geophysical and geologic techniques. If determined to be reasonably valid, these models may then be extended to other areas.

IDENTIFICATION OF SEISMOGENIC SOURCE ZONES

Source mechanisms for Eastern United States seismicity are poorly understood but are generally ascribed to several causes; reactivation of moderately steeply dipping brittle Triassic rift faults (Ramapo, Charleston, S.C.), movement on shallow dipping decollement faults (Charleston, S.C., Virginia seismic zone), concentrated stress around mafic-plutons (Cape Anne), reactivation of major crustal sutures. However to date none of the extant hypotheses have been proven totally applicable in any instance. In order to provide good probabalistic risk assessment for any area, seismic source zones need to be identified and mapped to depths within the earth's crust that generate the seismicity. Such correlation between hypocenters, commonly from 1 to 15 kilometers in depth in the Eastern United States can only be accomplished through integration of results of (1) geologic surface mapping (to identify potential seismogenic structures), (2) analysis of well-constrained instrumental data, (to establish focal mechanisms and depth), (3) *in situ* stress measurements (to constrain attitude of failure surfaces), and

(4) geophysical studies such as multichannel seismic reflection to track structures to hypocentral depths thus establishing correlation between near surface geologic features and seismic sources.

NECESSITY OF GEOLOGIC STUDIES OF SEISMOGENIC BASEMENT

It is clear that study of areas in which the seismogenic basement is exposed allows the greatest degree of correlation between geologic structure and seismic source zones. Ramapo, Central Va. Seismic Zone, New Brunswick, central New Hampshire are such areas. Other areas where seismogenic basement can only be sensed geophysically (Charleston) may allow reasonable models to be formed but these models will always lack the veracity of those developed where structural control can be extended from surface exposures to hypocentral depths. The results of the better constrained models derived from study of exposed seismogenic basement rocks, however, can be fed-back into the less constrained situations with profit. Charleston and Ramapo for example have enough in common, i.e., the potential of reactivated Mesozoic faults, that these two studies can and should mutually reinforce one another.

STUDIES IN THE RAMAPO SEISMIC ZONE AND THEIR BEARING ON SOLUTION OF THE CHARLESTON PROBLEM

A large body of well-constrained epicentral and hypocentral data is available in the New Jersey-New York area because of the detailed networks operated there by Lamont-Doherty and Woodward-Clyde, and the persistent low-magnitude (Mb 1-3) activity in and around the Newark Triassic-Jurassic basin. Aggarwall and Sykes (1978) called attention to the spatial association of this seismicity to the Mesozoic Ramapo fault and/or family of similarly oriented faults are currently being reactivated as reverse fault to produce current seismicity. The Ramapo model, therefore, calls for reactivation of Mesozoic normal faults is reverse faults and this model has been extended to Charleston.

Since 1978 detailed field mapping, fault definition mapping, trenching, coring, and correlation of the epicentral data by Ratcliffe has produced some unexpected results. The major results are:

1) Seismicity is not restricted to the Ramapo fault but is distributed across a 40 km wide zone roughly centered on the Ramapo fault.

2) Within the seismically active areas an unusually profuse zone of faulting of various ages is present. This is one of the most highly faulted areas in the Appalachians.

3) Seismicity is not restricted to areas of abundant Mesozoic faults but extends beyond the limits of Mesozoic brittle fractures.

4) The seismicity shows a tendency to be deeper in areas southeast of the Ramapo fault trace where hypocenters range from near surface to about 13 km.

5) Within this eastern zone of deeper seismicity fault plane solutions for many events contain two steeply dipping nodal planes, suggesting that faults have steep dips extend to these depths beneath the seismic zone and that detachment on a subhorizontal decollement is not likely.

6) Northeast-striking steeply-dipping surfaces are being reactivated as compressive faults.

7) The geologic framework of the seismic zone is dominated at the surface by faults of the nature cited in (6) and include Mesozoic faults that have formed by reactivation of older structures that penetrate the Proterozoic substrata beneath both Paleozoic and Mesozoic cover.

8) Trenching and core drilling of the Ramapo fault has failed to produce any evidence of near surface reactivation of the Ramapo fault itself as a modern reverse fault.

Thus, within the Ramapo seismic zone the origin of the seismicity is not clearly linked to Mesozoic faults. The seismicity, however, does seem to be confined areally and in cross section to fault bounded wedges of Proterozoic Y basement gneiss that form the floor and border rock of the Triassic Basin. Little seismicity occurs within the Mesozoic basin or beneath it, but extends through a broad zone in the basement rocks surrounding the Triassic-Jurassic basin. The seismogenic basement is cut by numerous faults of Paleozoic and Meosozoic age aligned along the NE structural and seismic grain. Most faults exhibit abundant evidence of reactivation at various times in the Paleozoic and Mesoozic.

These results suggest strongly that fracture patterns and faults in Proterozoic gneiss of the Hudson Highlands or faults bounding this material are sources of seismicity in the Ramapo area. The major advantage of the Ramapo area, in addition to recurrent activity, is the exposure over broad areas of this seismogenic basement.

A combination of vibroseis reflection profiling, gravity modeling, refraction studies in conjunction with surface mapping should allow detailed characterization of this seismogenic basement to depths of 15 km. Integration of these geophysical and geologic data with new crustal velocity models and consequent refinement of hypocentral data and focal mechanism should allow deterministic models for Ramapo seismicity to be developed.

At the present time, although a fault reactivation hypothesis seems correct, the available data do not point to a single fault or even family of faults as being the culprit. Rather, highly faulted basement rocks adjacent to a major Mesozoic Basin, are identified as the seismogenic source. Even at Ramapo alternate or even combinations of various fault models cannot be ruled out at present and several models are likely to be correct.

Many of the major geologic elements present at Ramapo, a Mesozoic Basin, fractured crystalline rocks, thrust bounded wedges of basement rock, etc., are present or inferred to be present at Charleston. My contention is that much can be learned about the origin of seismicity in poorly exposed areas such as Charleston from detailed studies of analogous areas where the seismogenic basement is available for study. Deterministic studies of Eastern United States seismicity should include development of testable models from well-exposed and well-instrumented areas such as Ramapo. These models may then be applied to less well constrained areas such as Charleston.

LARGE STRAIN EFFECTS OF THE 1886 SOUTH CAROLINA EARTHQUAKE

by

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The 1886 South Carolina earthquake was associated with both localized strain caused by liquefaction and systematic strain leading to permanent deformation on a large scale. These phenomena are strongest in the Charleston-Summerville area, but are also reported elsewhere in the Coastal plain of South Carolina. Joints, clastic dikes, faults and folds are relatively common structures in the post-late Cretaceous sedimentary wedge of the Coastal Plain. Some of these structures probably represent deformation associated with prehistoric earthquakes similar to the one in 1886. The 1886 strain effects and the structures in the sediments are of concern for three reasons. First they contribute specific elements to the estimate of earthquake hazard in the Coastal Plain, independently from any tectonic model. Secondly, they may provide information about the mechanism of the event in 1886. Thirdly, they may provide the timing and possibly other information about previous events similar to the one in 1886.

In this study we examine strain effects in the Coastal plain of South Carolina associated with the 1886 earthquake from data reported in Dutton (1889) and new data obtained from archival sources, mostly newspapers. The pronounced and widespread large scale deformation indicated by these data are unique for a known earthquake along the Appalachians/Atlantic seaboard. These strain effects are discussed in terms of 1) their direct implication for the kinds of damaging effects that can be expected in the Coastal Plain within a considerable range of epicentral distances from an 1886-like event; 2) mechanisms for these effects, juxtaposing the possible roles played, on the one hand by primary faulting in the 1886 event, on the other hand by deformation in the post-Late Cretaceous sediments by slumping and dewatering induced by shaking and liquefaction and high pore pressure; 3) the similarity between the type of deformation inferred from the reported 1886 effects and the prehistoric structures observed in the sediments.

Some of the coseismic effects of the 1886 earthquake indicate strain that is specially incoherent and non tectonic in origin. Water and sand were ejected from fissures and craterlets. Sinks were formed. These phenomena indicate localized differential movement of sedimentary material. In most cases the sediments involved were unconsolidated and partially liquefied, presumably by the seismic excitation. Liquefaction effects were very intense in the Charleston-Summerville area, were scattered elsewhere in the Lower Coastal Plain of South Carolina, and were also reported in the outskirts of Columbia, South Carolina, at the feather edge of the Coastal Plain wedge (Figure 1).

Other phenomena suggest coherent strain over large areas which may be tectonic. Changes in line-of-sight were independently reported in two localities near Augusta, Georgia, and in Columbia, South Carolina (Figure 1). Wide dry fissures were reported from several localities of the Upper Coastal plain of South Carolina (Figure 1). Fissures of this kind were allegedly the cause of the failure of the earth-filled dam near Langley (Figures 1 and 3).

Finally, the best constrained and most striking of the strain effects. The three rail lines radiating from Charleston, South Carolina, suffered extensive damage, partly as a consequence of soil failure (Figure 2). The branch directed toward the northwest (S.C.R.R.), however, was damaged exclusively by bucklings over a 25 km of the damage. We conclude that 5 meters is a conservative estimate of the ground shortening needed to account for this buckling of the rails (Seeber and Armbruster, 1981). This estimate is now strengthened by another similar estimate (17 feet of shortening) published in the Atlanta Constitution (Sept. 26, 1886) which we recently uncovered.

Some of these strain effects may be mainfestations of a wide field of deformation associated with NW extension near the Fall Line (NE-SW fissures cutting across Langley dam) and NW compression near Summerville (buckling of the rail) and possibly elsewhere in the Lower Coastal Plain of South Carolina. We have proposed a tectonic interpretation of such a strain field. According to the detachment activation model, a backward (toward the southeast) slip of the upper crust on shallow dipping Paleozoic faults would account for the neo-tectonic activity along the Appalachians. In this hypothesis the 1886 event would be associated with extension at the updip end of the rupture near the Fall Line and

It was simply as if some tremendous power had torn the earth apart . . . . The largest crack, was perhaps, two feet across . . . . Into one of these giant cracks a pole was lowered without reaching the bottom . . . . There had been no eruption and no extraneous under sand was found in the cracks . . . . It was through such cracks as these that the water made its way and swept the dam out of existence. (Atlanta Constitution, September 26, 1886).

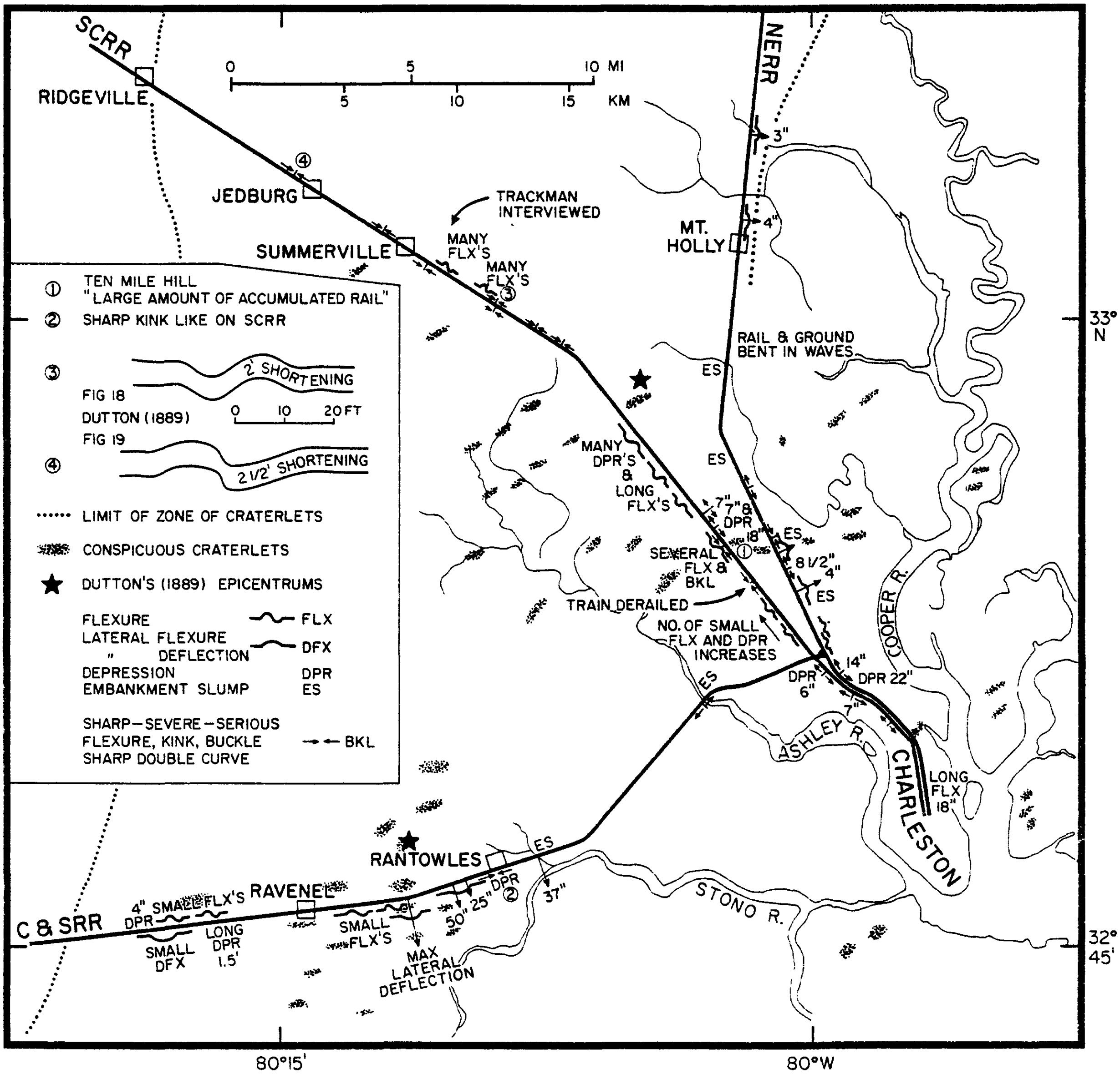

Figure 1.--Effects of the 1886 earthquake indicative of permanent coseismic strain. The final adjustment of the railroad tracks between Summerville and Charleston has been made, and just seventeen feet have been cut out. This represents the contraction of the earth between those two points, which are just twenty miles apart.

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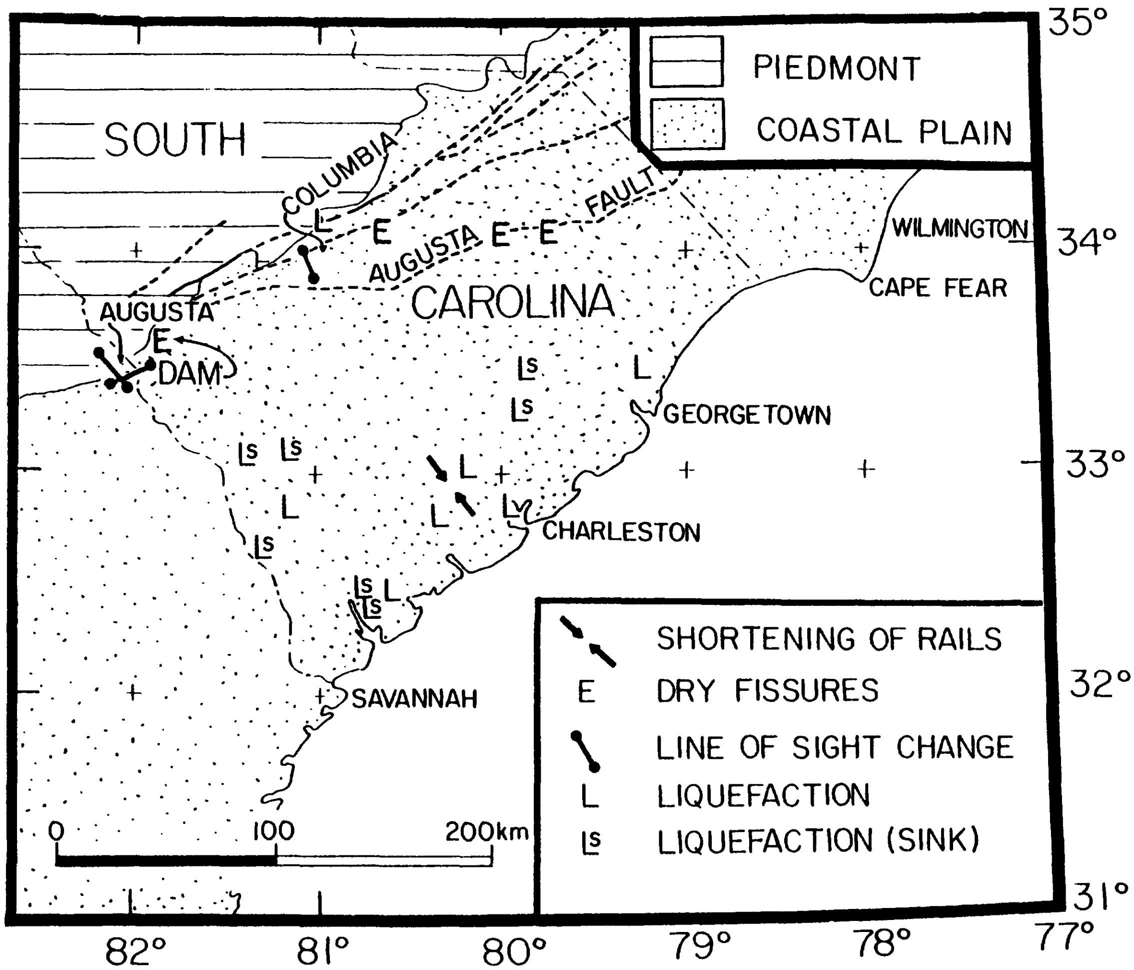

Figure 2.--Damage to railways in the Charleston-Summerville area in the 1886 Charleston earthquake (data from Dutton, 1889, p. 282-310). In a 25 km long portion (19-43 km from Charleston) of the South Carolina Railroad (SCRR) damage is exclusively by buckling of the rails revealing a northwest compressive strain event. Our original estimate of at least 5 meters of shortening (Seeber and Armbruster, 1981) was corroborated by the report in the Atlanta Constitution we recently uncovered (above).

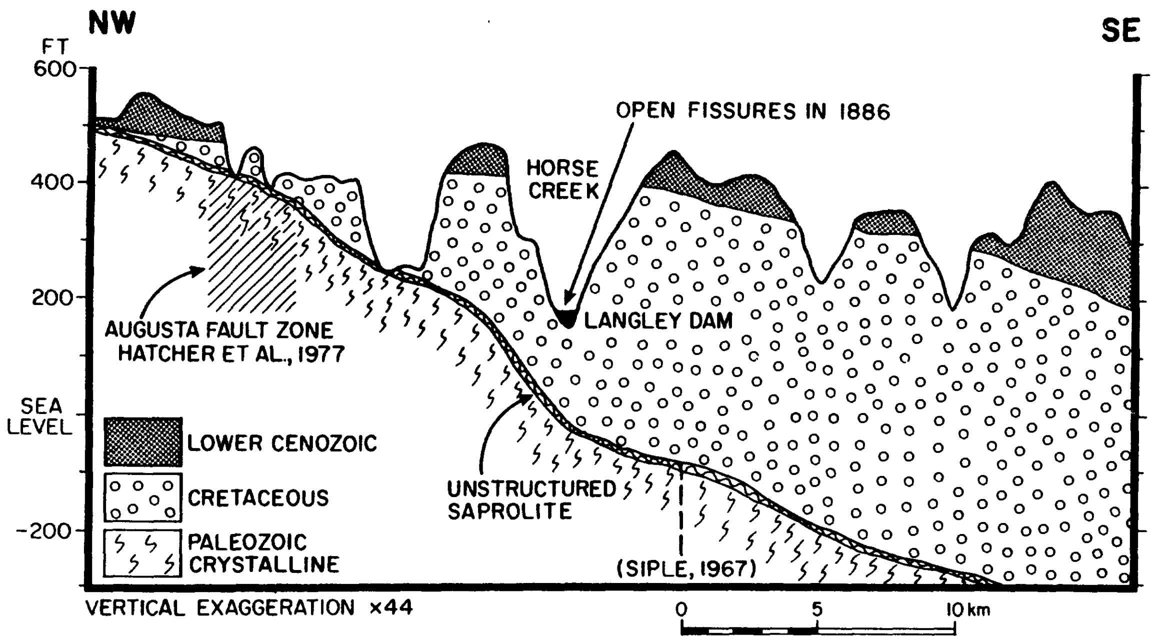

Figure 3.--Cross section through Langley Dam near Augusta, Georgia. Dutton (1889) in reporting the failure of this dam in the 1886 earthquake says that many fissures with widths up to several inches opened in the vicinity of the detritus created in 1886 can be found and trenched they could be compared to similar structures in the upper Coastal Plain which may be a result of pre-historic earthquakes.

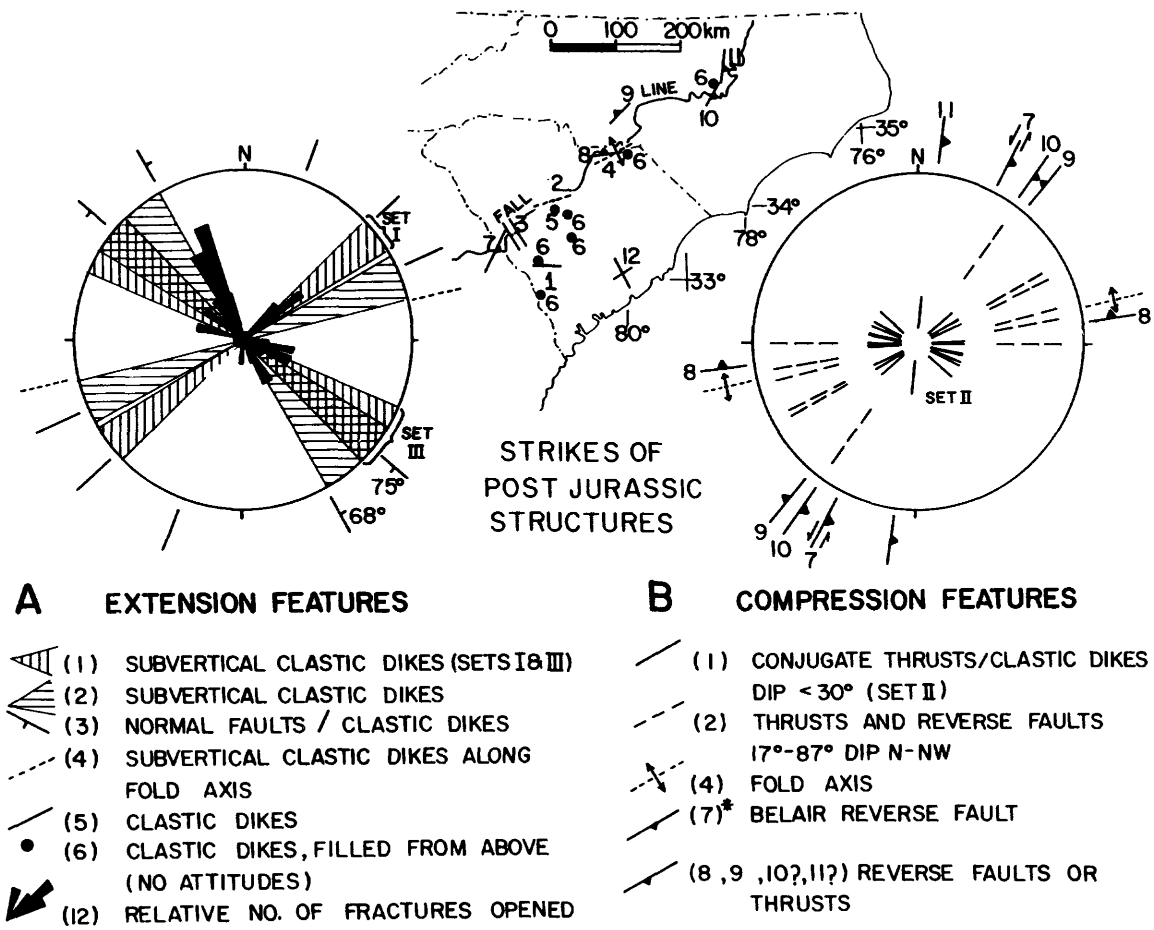

Figure 4.--Structures involving the post-Jurassic Coastal Plain sediments of Georgia, South Carolina, and North Carolina (Seeber and Armbruster, 1981). (Number refer to localities marked on the map.) Widely separated localities show a similar pattern of extensional and compressional features. For example, the orientation of clastic dikes at 1 and 2 is remarkably similar. This suggests a single mechanism acting over a wide area. The Belair fault (7) is the only surface structure of the Coastal Plain in the area shown for which the involvement of the basement is well demonstrated (indicated by an asterisk) (Prowell and O'Connor, 1978).

compression at the downdip end of the rupture near Summerville. Results from fission track dating indicate large post-Jurassic differential uplift across the Fall Line (Zimmerman, 1980) and suggest that this feature is tectonically controlled.

A non-tectonic interpretation of the large strain phenomena, however, is also possible and requires large scale differential movement of the Coastal Plain sediments with respect to the pre-Cretaceous rocks below (Seeber and Armbruster, 1981). A clay-rich saprolite is buried at the pre-Late Cretaceous unconformity at the base of the sediment wedge. This layer is gently warped and generally dips 0.3 - 0.5^{o} south-southeast. It is continuous and impermeable over large distances so that high pore pressure and salinity are maintained below this surface. The Cretaceous saprolite may partially loose cohesion when subjected to vibrations and pore-pressure transients induce by large earthquakes in the region and may effectvely decouple the sedimentary wedge from the substratum. Lateral displacements of this wedge, downdip on the unconformity, may account at least for some of the reported large strain in 1886 as well as for some of the structures observed in the sediments. In this hypothesis the gravitational collapse of the sedimentary wedge would be a secondary effect of the 1886 earthquake.

Many of the strain effects in 1886 can be expected to have generated recognizable structures in the sediments of the Coastal Plain: clastic dikes and pipes (ejection of sand and water from fissures and craterlets; dry fissures); folds and faults (changes in-line-of-sights; compression of the rails). It is reasonable to postulate that many earthquakes similar to the one in 1886 have generated similar structures. In fact, these kinds of structures are quite common in the sediments of the Coastal Plain (Figure 4). If a link between seismicity and structures in the sediments can be established, we may be able to learn about the seismicity from these structures. Vice versa, we may be able to learn about the genesis of these structures by studying the effects of the 1886 earthquake.

Stress direction can be inferred from some of the structures in the sediments. A number of Cenozoic faults, mostly reverse, have been documented near the feather edge of the sediment wedge. Zoback and Zoback (1980) used primarily data on these faults to infer a maximum horizontal principal stress directed across the

Appalachian strike in the Atlantic Coast province. Joints, however, are the most ubiquitous kind of structure in the Coastal Plain sediments. Often these joints contain injected clastic material and can be classified as clastic dikes (e.g., Heron et. al, 1971; Zupan and Abbott, 1975; Secor, 1980). Joints and clastic dikes are sympotmatic of a minimum principal stress axis normal to the joint surface. In the Coastal Plain subvertical joints and clastic dikes often form quasi-perpendicular sets suggesting one or more reversals of principal stress axes (Engelder, 1980; Seeber and Armbruster, 1981).

Finally, the data which indicate that the 1886 earthquake was associated with large permanent deformation over a large area are directly pertinent to seismic hazard. Large permanent deformation can be associated with severe damage and wide distribution of this type of this type of effect that can be expected from 1886-like events, is of concern independently from the mechanisms involved.

In summary, large-scale strain effects coseismic with the 1886 earthquake were widespread over the Coastal Plain of South Carolina. The data suggest northwest shortening amounting to several meters over 25 km near Summerville and hint at northwest extension near the Fall Line. How much, if any, of these effects are the direct result of the primary fault movement, and how much are secondary effects remain an open question. This same ambiguity affects the interpretation of structural features in the sediments in terms of tectonic stress. We feel that a combined study of structures in the sediments and 1886 strain effects would go a long way to solve this ambiguity, yielding valuable constraints on the 1886 event, on prehistoric large earthquakes, on the significance of Cenozoic strucutral features in terms of tectonic stress, and on the direct implications of strain effects for earthquake hazard.

IS SOUTH CAROLINA SEISMICALLY ACTIVE ON A NORTHWESTWARD PROJECTION OF THE BLAKE SPUR FRACTURE ZONE?

by

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INTRODUCTION

A hypothesis to explain the seismicity of the Charleston region is that of seismic reactivation of a large, narrow, northwest-trending weak zone that crosses most or all of South Carolina (see review by Sykes, 1978, Figure 2 and p. 655-658; Talwani, 1983, this volume; Barosh, 1983, this volume). The zone is usually inferred to have formed in North American cratonic crust, propagated across the Appalachians, and nucleated the Blake Spur fracture zone (BSFZ) where two Mesozoic rift segments met but were decoupled from each other at the weak zone. Less commonly the BSFZ is suggested to have propagated northwestward into continental crust in Mesozoic or later time. The main basis for both forms of the hypothesis is the observed alignment of the BSFZ with the diffuse seismicity of Bollinger's (1973) South Carolina-Georgia seismic zone (SCGSZ).

In some forms of the hypothesis, a small circle of the sort used to model transform faults is fitted to the BSFZ and shown to project northwestward, through or near clusters or alignments of epicenters as mapped by various authors. All forms of the hypothesis state or assume that the weak zone can be recognized by examination of presently available geological, seismological, and geophysical maps.

New data, analytical results, and interpretations contradict this hypothesis of a narrow weak zone in four ways.

OFFSHORE GEOPHYSICAL DATA

Results of extensive and detailed geophysical investigations offshore from South Carolina are summarized by Behrendt and others (1983), Klitgord and others (1983), Dillon and others (1983), and Dillon and McGinnis (1983). About 150 km offshore from Charleston, a northeast-trending basement hinge zone coincides with the eastern edge of the Brunswick magnetic anomaly (Klitgord and others, 1983, Figure 2). Southeast of the hinge zone lie marginal basins that are separated from each other by the northwestern end of the BSFZ (Klitgord and others, 1983, Figure 1; Dillon and others, 1983, Figure 6). The investigations found no evidence that the BSFZ exists northwest of the hinge zone (Klitgord and others, 1983, p. P5).

Klitgord and others (1983, p. P5) conclude that the hinge zone, marginal basins, and BSFZ all originated in Early Jurassic time, as Triassic rifting, west of what is now the hinge zone, gave way to Jurassic and younger drifting, localized east of what is now the hinge zone. Thus the hinge zone marks the western edge of crustal blocks that became partly or wholly decoupled from each other during the start of Jurassic drifting. The BSFZ and other fracture zones nucleated at the irregularities in the drift-stage continental edge that were caused by the decoupling. The decoupled blocks subsided at different rates to form separate marginal basins. The fracture zones grew eastward as oceanic lithosphere accreted to the trailing continental edge of the drifting North American plate, at or near the eastern edges of the blocks that support the marginal basins.

Thus, at the scales of maps that are able to show South Carolina, the western end of the BSFZ, and the intervening continental margin, fracture zones nucleated at points. Those points are the intersections of (1) a line, the hinge zone, that separates rift-stage crust of Triassic and greater age from drift-stage crust that deformed in Jurassic and later time, with (2) lines that extend east from the hinge zone, across which pairs of marginal basins were decoupled during drifting. The present orientation of a fracture zone has been determined by the orientation of relative plate motions during Jurassic and younger drifting, and is in no way related to the orientation of the decoupling line at whose eastern end the fracture zone nucleated.

In fact the position and orientation of the decoupling line that gave birth to the BSFZ are revealed by structure contours atop the presumed postrift unconformity (Dillon and others, 1983, Figure 6 and p. N5), and less clearly by contours of estimated depths to magnetic basement (Dillon and others, 1983, Figure 7). Dillon and others (1983, p. N5) suggest that the decoupling line marks the location of earliest transform faulting. Under the weak-zone hypothesis, that decoupling line would represent the landward projection of the BSFZ. If there were a reason to project the decoupling line landward, the projection would intersect the coastline at or south of the Georgia-South Carolina border, at least 100 km from the seismicity of the Charleston area.

Thus there is no evidence that the BSFZ extends to within about 150 km of land. Even if it did, it would miss the Charleston area by at least 100 km.

OFFSHORE SEISMICITY

No seismicity is known to have occurred in the 150 km or so between the coast and the above-mentioned hinge zone offshore from South Carolina. Two felt events were originally located offhore, but improved locations for those events now lie onshore, near Middleton Place-Summerville (Dewey, 1983, Figures 1 and 2). Through the 1970's offshore detection thresholds within about 100 km of the South Carolina coast decreased from about magnitude 4.0 to as low as 2.0, without offshore events being detected (Tarr and Rhea, 1983, Figures 3, 4, and 5). No earthquakes are clearly known to have occurred offshore since the beginning of the historical record in 1698 (Tarr and Rhea, 1983, Figure 1). In June, 1980, three downhole seismometers were installed along the coast of South Carolina to seek offshore activity. No earthquakes have thus far been detected by those sensors down to a detection threshold of about magnitude 1.5 (S. B. Rhea, oral commun., June 1983).

ONSHORE EPICENTERS

Epicentral locations contain no clear evidence of a northwest-trending alignment crossing South Carolina. The diffuse SCGSZ of Bollinger (1973) comprises epicenters that mostly have locational uncertainties too large to allow a rigorous test of a hypothesis of alignment (Reagor and others, 1980; G. A. Bollinger, oral commun., 1983). Earthquakes recorded since March, 1973, by the

South Carolina network show clusters of epicenters in the Coastal Plain near Bowman, Middleton Place-Summerville, and Adams Run, and diffuse seismicity in the Piedmont province, but no alignment (Tarr and Rhea, 1983, Figure 5).

Bollinger and Mathena (1982, Figure 12; reproduced in this volume by Barosh) map epicenters of earthquakes that occurred in the Southeast from July, 1977 through June, 1982. In general those epicenters are more accurately located than those available to Bollinger (1973), because of reduced spacing and improved azimuthal distribution of seismic stations and development and use of local velocity models. However, any statement that there is a diffuse epicentral alignment between the Charleston region and northwestern South Carolina or eastern Tennessee is a statement of opinion that is based on individual perception. For example, my perception differs: I see no such alignment on the map of Bollinger and Mathena (1982). Instead I see a diffuse cluster of epicenters in the northwestern third of South Carolina, with three small and apparently unrelated clusters in southeastern South Carolina and central Georgia, and a larger cluster in eastern Tennessee that is elongated northeast-southwest. Which, if either, perceived pattern is real cannot be decided without a carefully designed and controlled, double-blind experiment using several independent and unbiased operators, or still better a properly designed statistical test. I know of neither.

Other considerations suggest that it may still be premature to interpret spatial patterns in state-wide epicentral maps of either historical earthquakes or small instrumental events. Newspaper research by Armbruster and Seeber (this volume) demonstrated the severe incompleteness of a selected portion of the historical record. G. A. Bollinger and P. Talwani (oral and written communs., 1983) suggest that the catalogue of small, instrumentally-determined events still contains quarry blasts and perhaps highway blasts. Finally, the detection threshold of small events has decreased markedly since 1970, but remains nonuniform across South Carolina (Tarr and Rhea, 1983, Figures 3 and 4). On the scale of the state, both error ellipses and contours of smallest detectable magnitudes are elongated to the northwest and southeast. The elongation could bias epicentral maps towards apparent alignment in those directions. (Such bias would not occur in small areas with dense networks, such as those near Charleston.)

However, improved locations for 18 instrumentally located earthquakes that occurred in South Carolina and Georgia, from 1945 to 1976 and which have magnitudes of at least 3.0, do show a striking northwest alignment across the state (Dewey, 1983, Figure 2). Several people, including me, have remarked that the alignment appears to support the existence of a narrow, northwest-trending weak zone. However the alignment is not statistically significant, according to the following test.

The test used is a randomization test (Conover, 1971, p. 357-364; Mosteller and Rourke, 1973, p. 12-15; Bollinger and Wheeler, 1982, appendix D, p. 78-79). It gives the descriptive level of significance p of an alignment, that is, the probability that the perceived alignment could have arisen by chance. Small values of p suggest that their alignments are real. For the randomization test as Bollinger and Wheeler formulated it,

$$p = 1/C(n,r) = r!(n-r)!/n!$$

where the alignment to be tested involves r points out of a sample of n points. The null hypothesis is that the perceived alignment of r points arose by chance when the sample of n points was chosen from a population containing no real alignments. Here, the population comprises all earthquakes that have occurred in the study area and which would have been relocatable by the methods of Dewey (1983).

The test as used here is subject to the following constraints. First, it will usually underestimate the level of significance p, because the r aligned points must be selected by inspection of the sample rather than before sampling. That is, the value calculated for p always reflects the structure of the sample rather than the structure of the population. If the alignment to be tested is identified by inspection of the sample, as in this case, then any differences between this particular sample and the population are more likely to distort p toward small values than toward large values. That is because if the sample of earthquakes that Dewey (1983) mapped is not representative of the population, it is probably because the population contains a less striking alignment of epicenters, rather than because it contains a more striking alignment than seen in the sample. The usual way to avoid such bias of p is to formulate hypotheses by inspecting one sample, and to test the hypotheses on a second sample. Unfortunately no second sample is available, and as seen below the available sample is too small to divide. The other, less common protection against an unrepresentative sample is a procedure called jackknifing (Mosteller and Tukey, 1977, p. 133-163). Jackknifing also cannot be used here because it requires more than one pair of values of r and n (Mosteller and Tukey, 1977, p. 136 and 145-148), and only one pair is available. The result of all that is that the value calculated for p may be biased toward small values but probably not toward large values. Thus the test will be conservative the way I shall use it.

Second, the test is able to achieve the smallest p values for $r = n/2$. The test loses that resolving power but remains valid as r approaches 1 or n. Third, the test is not sensitive to the areal density of the points, and so may not detect a non-random alignment that involves a few closely spaced points. Thus the test should be applied only to alignments that span much of the state; this one does. Fourth, because of the difficulty of quantifying the concept of alignment, the test can evaluate only the one most striking alignment that is seen in a sample of n points. Thus it is necessary first to determine that other workers would also independently choose the same alignment, as the one that is most likely to be non-random; as already mentioned, several other workers have also remarked on this alignment, and on it alone.

For many of the epicentral locations recalculated by Dewey (1983), confidence ellipses overlap. The most probable location for each earthquake is at the center of its ellipse, but it could have occurred anywhere within the ellipse with a probability of 0.90. Thus two earthquakes can be regarded as coincident if each ellipse includes the center of the other. Similarly, if an ellipse includes a point with no locational uncertainty, such as a portion of a reservoir, the earthquake may have occurred at that known point. The result of those criteria is that, for evaluation of a suspected state-wide alignment, two or more coincident epicenters count as only one point. That is appropriate because we are testing an alignment of separate sources, not an alignment of repeated reactivations of the same sources. Second and subsequent earthquakes at the same source add no new information. Bollinger and Wheeler (1982, appendix D, p. 78-79) did not consider coincident epicenters or hypocenters when they evaluated the Giles County seismogenic zone. However only 2 of their events coincide, so that would increase their reported p value only from 0.002 to 0.003.

Of the 18 earthquakes relocated by Dewey (1983, Figure 2), 9 collapse into 3 points that represent the clusters near Adams Run, Bowman, and Middleton Place-Summerville. Six earthquakes occurred at reservoirs after filling, so Dewey (p. Q7-Q8) suggests that the earthquakes may have been induced by the fillings. That leaves 6 points: the 3 clusters, and the earthquakes of 1945.07.26 in central South Carolina, 1969.12.13 in northwestern South Carolina, and 1976.12.27 in eastern Georgia. The first 5 points align, so
$p = 0.17$. Thus because some clustered earthquakes contain duplicate information, and because others may have been reservoir induced, the remaining sample is too small to demonstrate the existence of a northwest-trending alignment of seismic sources across South Carolina.

Testing the perceived alignment of 5 of the 6 sources by regression rather than by the randomization test produces similar results. First, the 6 sources have locational uncertainties on the order of several tens of kilometers (Dewey, 1983, Figure 2). Bolt (1978) notes that the effect of uncertainty in the independent variable is to decrease the significance of an association, that is, to increase the value of p. Because both coordinates have locational uncertainties, Bolt's remark applies regardless of the choice of independent and dependent variables.

Second, if locational uncertainty is ignored for the moment, the 5 aligned sources fit a least-squares regression line at p less than 0.005, whether latitude is regressed on longitude or vice versa. However the appropriate analogy to the randomization test is to regress all 6 sources within Dewey's (1983) study area, rather than choosing 5 by inspection. Then $p = 0.234$. The consideration of Bolt (1978) makes p exceed 0.234. Thus regression too fails to detect a significant alignment among Dewey's relocated epicenters.

GEOLOGIC EVIDENCE

As mentioned in the introduction, the two main supports for a narrow, state-sized, northwest-trending weak zone arise from marine geophysical and continental epicentral data. As discussed above, recent investigations have removed these supports. It remains to consider whether there is geologic evidence onshore for the existence of such a weak zone.

In its simple forms, the hypothesis characterizes the weak zone as a high concentration of faults or other fractures, or of structural anomalies such as folds that are restricted to a small area, or bends in geologic contacts or in structural boundaries. The width of such a zone would be small compared to the size of South Carolina, perhaps several kilometers or tens of kilometers. Because structural anomalies of various kinds are common in multiply-deformed terranes such as the Piedmont province, enough such anomalies must be found to demonstrate that they align in a nonrandom way, and the anomalies must not be readily explainable by structural and other orogenic processes that are known to occur normally during the evolution of rock masses like the Piedmont province. Such an expression of a weak zone should be detectable by geologic mapping, geophysical modelling, or both. The few structural anomalies that have been found have other explanations and are too few to demonstrate an alignment (D. T. Secor, oral commun., 1983). Small-scale geologic maps also show no evidence of a narrow weak zone (King and Beikman, 1974; Figure 1 of Hatcher and others, 1980; Overstreet and Bell, 1965).

Small, northwest-striking faults, dikes, or both are common in the exposed Paleozoic areas of South Carolina, as elsewhere in the Appalachians (for example, see King and Beikman, 1974). Some exposed Mesozoic basins contain and are partly bounded by several northwest-striking faults that may have remained weak, because no regional events have occurred since their formation that might have healed those faults to the strength of unfractured rock. It is reasonable to expect such cross faults to occur in or at the ends of some of the Mesozoic basins that are being found beneath the Coastal Plain. However the presence of such small faults and dikes is not evidence for a state-sized weak zone. Even if such faults or dikes appeared to align across the state, that alignment would have to be shown to be distinguishable from a chance concentration of randomly distributed structures.

The known and inferred geologic history of the Southeast makes it unlikely that a narrow weak zone could have been preserved as crossing the Appalachians from the Precambrian craton on the northwest to Mesozoic oceanic crust on the southeast.

Klitgord and others (1983, p. 5) explain why the BSFZ would probably not have grown northwestward, by forming first in Mesozoic oceanic crust and then propagating into the Appalachians and craton. That conclusion arises from the origin of the BSFZ, which is summarized in a previous section on Offshore Geophysical Data.

To have grown to the southeast, by starting in the craton, such a weak zone would have to have persisted through a barrage of island arcs, microcontinents, and diverse lithospheric shreds and fragments that were swept into North America as the Iapetus Ocean and related basins and seas closed throughout the Paleozoic (Williams and Hatcher, 1983; see other papers cited by Bollinger and Wheeler, 1982, p. 20-21; compare also Coney and others, 1980, Hamilton, 1978, and Karig, 1983). The weak zone would also have to have survived repeated physical, thermal, and chemical reworking as the Appalachians accumulated and deformed internally (see review by Hatcher and others, 1980), as well as dismemberment by any strike slip like that farther northeast, which is inferred to have totalled as much as hundreds or thousands of kilometers (Kent and Opdyke, 1978; LeFort and Van der Voo, 1981). The geological, geophysical, or seismological recognition of any such weak zone that survived until now could probably only arise from knowledge of the orogenic evolution of the southern Appalachians, at a level of detail and understanding that may be anticipated (Hatcher and others, 1980) but which does not yet exist.

A narrow weak zone could have avoided the perils described in the last paragraph by forming in the Mesozoic, after the Appalachians had formed. In fact, that is just when the BSFZ did form, as summarized in a previous section on Offshore Geophysical Data. That section also explains why such a Mesozoic weak zone is unlikely to be associated with the seismicity near Charleston, or to extend as far northwest as the coastline of South Carolina.

There remains one kind of weak zone that is geologically reasonable, though presently undocumented, and whose formation, evolution, and present characteristics might be consistent with the known and probable geologic complexities of the southern Appalachians. Such a hypothetical weak zone would be broad and diffuse rather than narrow, perhaps the width of the state of South Carolina. It would have grown southeastward throughout the Paleozoic development of the Appalachians, as island arcs and other terranes accreted to North America at an offset in the lapetan continental margin. They could have molded themselves to the shape of that offset, or overthrust it and draped themselves over it, so that the original offset propagated outwards, in the irregular form of successively developed patches of unusually intensely faulted rock. There may be demonstratable examples of that process and its geologic record elsewhere in the world, for example in western North America, Alaska, or the southwest Pacific. One may also suggest that the BSFZ probably did nucleate at some structural or geometrical irregularity within Pangea. However none of those postulates of hypothetical structure constitutes evidence that such a wide, diffuse, weak zone does exist in South Carolina, and without such evidence it seems unnecessary to retain the hypothesis for further testing.

CONCLUSIONS

1) The hypothesis of seismic reactivation of a narrow, state-sized, northwest-trending weak zone fails for South Carolina, because the BSFZ does not appear to affect or exist in continental crust landward of the offshore hinge zone, because the hypothesis has not been shown to be compatible with what is known or probable about the geologic evolution of the region, and because epicentral locations do not indicate such reactivation.

2. Because this may be the first hypothesis that can be discarded, of the many offered to explain Charleston seismicity (see list by Pomeroy, this volume), it is worthwhile to note the sources of the information that allowed such a comparatively clear-cut result. Each of the following has been necessary:

   a) accurate epicentral locations and years of monitoring by the South Carolina network and by regional networks,

   b) focused instrumental and analytical investigations, such as the installation and operation of down-hole seismometers along the coast and Dewey's (1983) relocation work,

c) collection, analysis, and interpretation of large sets of marine geophysical data,

d) collation and interpretation of results of a large amount of diverse geological work on the evolution of the southern Appalachians and selected other areas around the world, and

e) abundant discussion that ranged from the dispassionate to the rancorous, about matters that often seemed arcane or trivial at the time. Although evaluation of other hypotheses can probably be more focussed and perhaps more efficient than has been the case for this hypothesis, I see no grounds for expecting those other evaluations to be much simpler, quicker, or straightforward.

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DETERMINING THE CAUSE OF THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE

by

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INTRODUCTION

Determining "the cause" of the 1886 Charleston, South Carolina, event will have a significant effect on how we perceive seismic hazards in the Eastern United States. Presently, the cause of the Charleston Earthquake is not known and it is uncertain whether it can occur elsewhere in the Eastern United States. That uncertainty was underscored by the USGS 1982, letter clarifying their position on the Charleston event. Although Charleston is unique on the basis of seismicity, geologic structures known in the Charleston region occur elsewhere in the eastern seaboard. If the Charleston event was "caused" by one of these structures in Charleston, then there is the possibility that it could occur at other locations in the Eastern United States.

Our perception of seismic hazard from the Charleston event depends strongly on which structures it can migrate to. An example is the difference in hazard between the decollement and the Triassic basin hypotheses. The decollement, (eastern overthrust belt), occurs over much of the eastern seaboard. If it is determined to be the cause of the Charleston event then the hazard is "smeared out" throughout the very large source zone, there would be a very low probability of strong ground motion at any specific site. The Triassic basin hypothesis presents a distinctly different situation: the basins occur in several places in the eastern seaboard. The hazard is concentrated in and around the several discrete source zones. There would be a much higher probability of strong ground motion near these zones than in surrounding regions (although the absolute hazard may be low). The cause of the Charleston event consequently has a significant effect on how we perceive the seismic hazard in the Eastern United States.

WHAT CONSTITUTES CAUSE

The establishment of cause of the Charleston event is not just the discovery of a structure in the approximate epicentral area; there are many structures already defined. It is necessary to establish that there is active movement along the fault surface and, in order to completely understand the event, the mechanism that causes the seismicity must be understood.

In Charleston a number of structures exist in the area, however, no unambiguous correlation exists between observed structures and earthquake epicenters. Furthermore, none of the faults have been identified as active. At present, the cause (i.e. mechanism of stress concentration) is completely unknown.

HYPOTHESIS TESTING

The complete understanding of the cause of the Charleston earthquake will require the determination of 1) the structure responsible for the earthquake, 2) the strain responsible for the seismicity (i.e. the movements along faults), and 3) the mechanism of stress concentration in the epicentral area.

Although there are numerous kinds of geological and seismological information that can be obtained about the crust in the Charleston area, we want to obtain the kinds of information that will allow us to differentiate among the proposed hypotheses. In establishing a program to test the various hypotheses, we must consider what critical information can be obtained by each technique as well as what critical information cannot be obtained. In other words, the capabilities and limitations of the investigative techniques must be matched with the information needed to distinguish among the various hypotheses. The purpose of this session is to discuss and determine the information that can be obtained by the various geological and geophysical investigations and how that information can be used to distinguish among the various Charleston hypotheses. The following questions and problems are meant to stimulate discussion on the three points above and are not meant to be a complete or definitive list.

With regard to the structure responsible for causing the earthouakes:

1) Seismic reflection profiling is a powerful tool for defining faults with reverse or normal movement. But, how can we identify a strike slip fault? What potential field methods would be best?

2) What is the value of a borehole considering the three criteria for understanding the Charleston earthquake? Is the data to be gained from a borehole worth the extremely high cost? Will it help distinguish among competing hypothesis?

3) What information can surface mapping provide where seismicity occurs at depths of 5-8 and 12-13 km? How can surface mapping help to distinguish among competing hypotheses or help identify the structure on which the Charleston earthquake occurred?

4) Part of the proposed investigations is to investigate structures exposed in the Piedmont, which are similar to structures identified in Charleston (i.e. Ramapo fault system). What benefit will we get from this? If basement in the two areas originated and was deformed on different plates (for example, North American vs. African, etc.), will the results of these investigations be meaningful?

5) Through the years, as a previously unidentified structure has been defined in the Charleston area, a new hypothesis would result. Is it possible that several rather than just one may be right, and that the seismicity occurs because of the presence of several structures and their relationship to one another?

6) What information would we gain from a study of regional geomorphology along the lines developed by John Hack in coming to a better understanding of the neotectonics of the Charleston area?

7) What information would be gained from studies of the Pleistocene deformation of shorelines that overlie Cenozoic structures such as the Cape Fear Arch, Southeast Georgia Embayment, and the Peninsula Arch?

With regard to the strain responsible for the seismicity:

1) What types of studies will determine if a particular structure is active?

2) How can we improve the accuracy of our fault plane solutions? Do we need improved velocity models?

3) What information can we gain from surface geodetic measurements to help us understand strain deeper than 5 km? What types of surface geodetic measurements are most effective from a scientific and cost viewpoint?

4) How does the presence of local major structures such as the northwest striking southeast Georgia Embayment and Cape Fear Arch perturb the regional stress regime? How does the subsidence of the Southeast Georgia Embayment superimposed on the ongoing regional tilting to the southeast of the Coastal Plain effect the regional stress and strain in the Charleston area?

With regard to the mechanisms of stress concentration:

1) What types and how extensive an in-situ stress measurement program do we need to give us a sufficient understanding to choose among the competing hypothesis? Considering the depth to basement the capabilities and limitations of the techniques? What is unique, with regard to the state of stress for each major hypothesis that can be used for hypothesis testing? What information can we obtain from a limited number of in-situ stress measurements to aid in differentiating among the competing hypotheses?

2) What other studies will help us understand the state of stress?

4) What additional information could be obtained from improving the seismic networks and the analysis of the seismic data?

The above comments and questions are just meant to stimulate discussion and to illustrate the types of questions we should ponder in discussing what type of information should be obtained in order to distinguish among the several competing hypotheses.

UNIQUENESS OF CHARLESTON

In order to to have confidence that the Charleston region is seismically and geologically unique, something unique about the structure, activity or state of stress will not only have to be demonstrated, but its absence elsewhere in the eastern seaboard will have to be confirmed.

INTRAPLATE EARTHQUAKES, CRUSTAL DEFORMATION, AND IN-SITU STRESS

by

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INTRODUCTION

The geologic causes and controlling mechanisms of Charleston, South Carolina, type earthquakes along the east coast are best discussed from the perspectives of crustal deformation and in-situ stress. In this paper, up-dated data on the intraplate stress field in the Eastern United States is reviewed and the interaction between the intraplate stress field and active faults is considered as a basis for discussing models of intraplate seismicity. Finally, a hypothesis is discussed that large intraplate earthquakes are associated with zones of localized deformation in the lower crust which can be identified using geodetic strain data. If correct, this hypothesis suggests a manner in which future zones of potentially large intraplate earthquakes can be identified.

IN-SITU STRESS

Large and damaging intraplate earthquakes result from the interaction of in-situ stress and major faults in the earth's crust. To understand where such earthquakes are likely to occur in the future, it is necessary to understand both the nature of the faults upon which they occur and the forces driving the fault motion. The majority of in-situ stress data along the eastern seaboard from Virginia northward support the existence of a distinctly different stress field than the regional northeast-southwest compression of the mid-continent area (Figure 1, modified from Zoback and Zoback, 1980). Northeast trending reverse faults in the Atlantic Coastal Plain, the majority of available earthquake focal-plane mechanisms, and a few in-situ stress measurements at depth all indicate that approximate northwest-southeast compression characterizes the northeastern Atlantic coastal area. Reliable stress data are quite sparse in the Southeastern United States however. In the Charleston area itself, northeast compression or north to northeast striking faults is

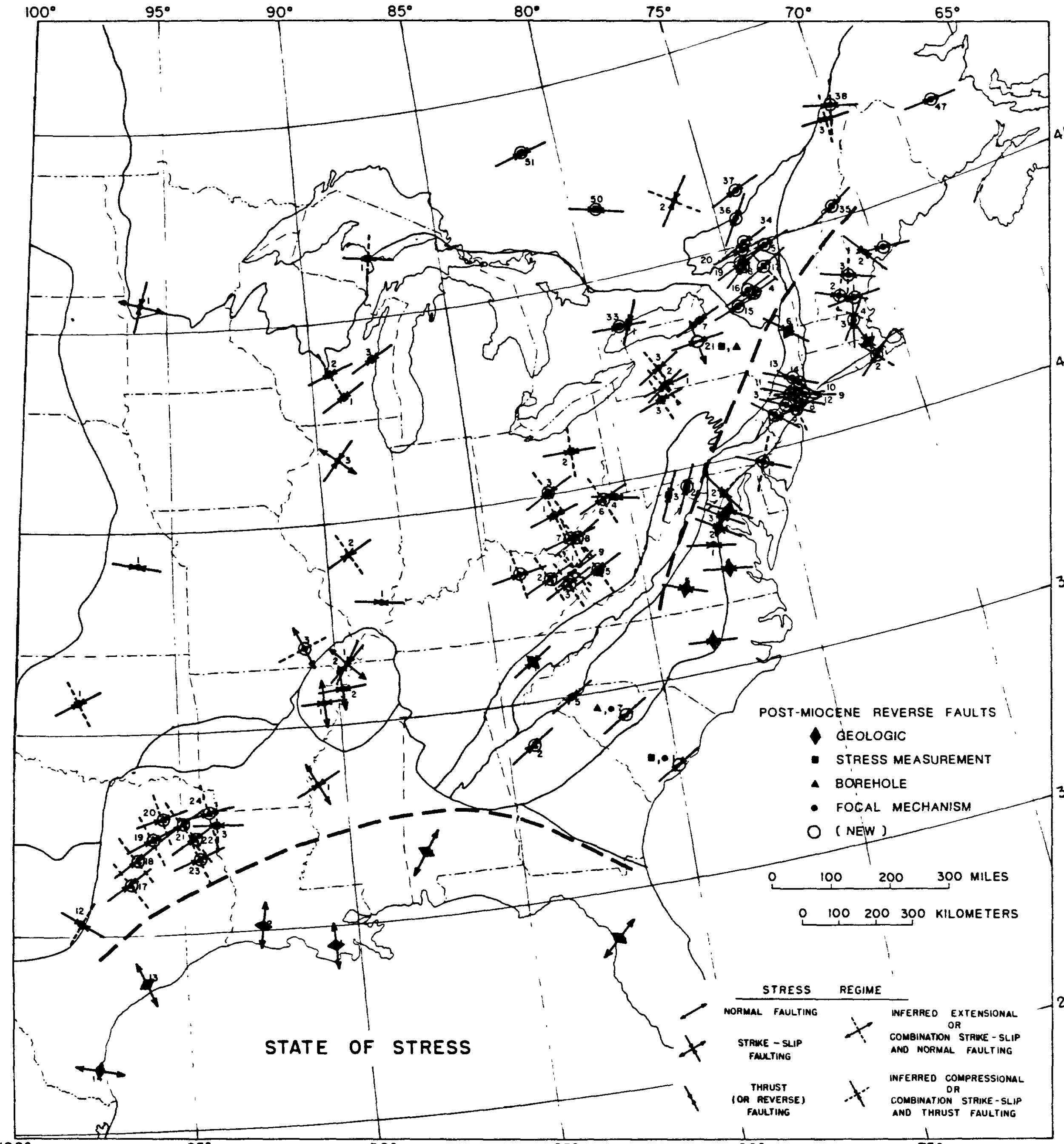

Figure 1.--Updated map of stress field indicators in the Central and Eastern U.S. (modified after Zobcak and Zoback, 1980).

indicated by composite earthquake focal plane mechanisms (Talwani, 1982). An attempt that is now underway to determine the orientation (and extent) of the stress field near Charleston mapping wellbore breakouts with an ultrasonic borehole televiewer. Using this method, data from wells at Monticello reservoir (near Columbia, South Carolina) indicate northeast compression, so does data from a well near Atlanta, Georgia, and interpretation of impression packer data from a well near Clubhouse Crossroads also supports northeast compression. Thus, as shown in a generalized form in Figure 2, the east-northeast compressive stress field of the mid-continent region can apparently be extended into the Southeastern United States If correct, this implies that the forces responsible for the Charleston earthquake may be similar to those responsible for the large intraplate earthquakes in the New Madrid, Missouri area, but dissimilar to those responsible for earthquakes along the northeast Atlantic seaboard.

An important unresolved question, is the nature of forces responsible for northeast trending Cenozoic reverse faults in the Southeastern United States (Prowell, 1983; Wentworth and Mergner-Keefer, 1982). Unless there is considerable lateral motion on these faults, the current stress field is incompatible with the observed fault motions. One obvious explanation of this inconsistency is a change in the orientation of the stress field since the time of faulting (which in most cases is Eocene).

Additional wellbore breakout data will soon be available from the Charleston area as well as the Macon and Brunswick areas in Georgia. These data will provide an important constraint on the stress field in the Southeastern United States

INTERACTION OF STRESS WITH FAULT

An important issue is the manner in which the stress field interacts with certain types of faults to cause large intraplate earthquakes. In the New Madrid seismic zone, for example, a major implication of seismic reflection data gathered both by the Geological Survey and private industry are that earthquakes are occurring along recurrently active faults in response to a regionally uniform east-northeast-west southwest compressive stress field (Figure 3, after Zoback and Zoback, 1981). Also, the northeast trending

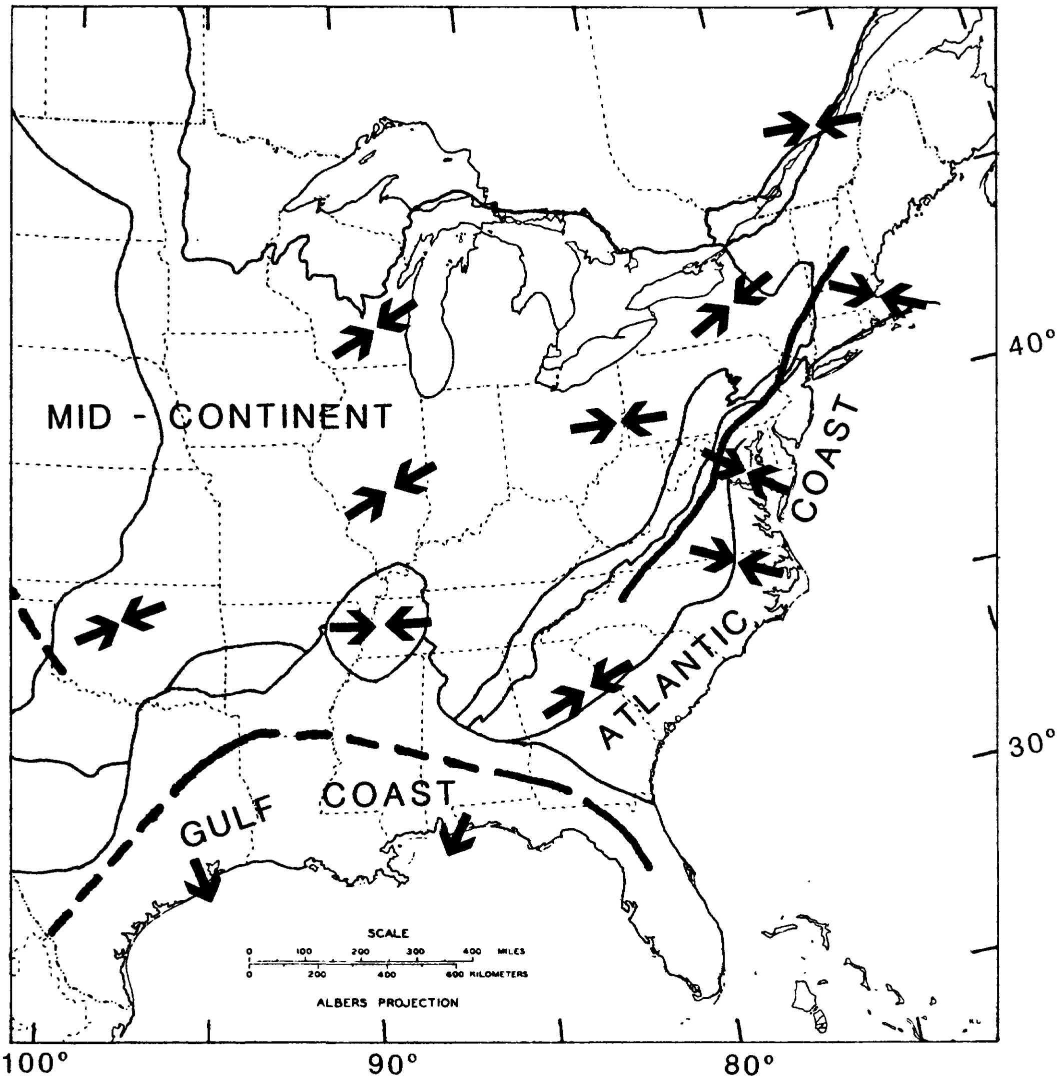

Figure 2--Generalized stress map of Central and Eastern United States (modified after Zoback and Zoback, 1990). Relatively uniform northeast-southwest compression seems to persist through the mid-continent and Southeastern U.S.

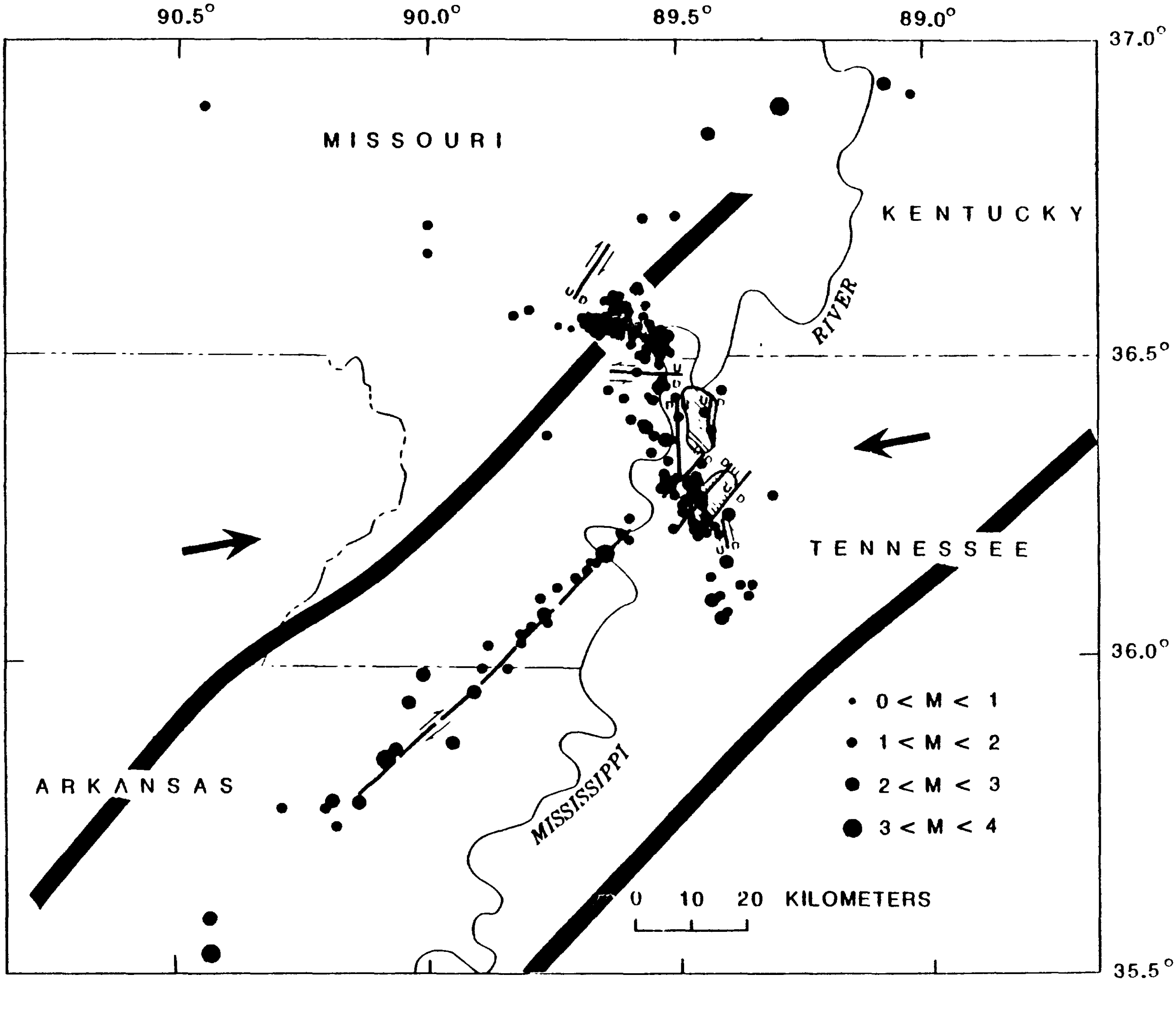

Figure 3.--Seismotectonic map of the New Madrid, Missouri, seismic zone (from Zoback and Zoback, 1981). Current seismicity is occurring within a late Precambrian-early Paleozoic mid east-northeast compressive stresses. Faults were found using seismic profiling.

right-lateral strike slip fault zone along which the three 1811, 1812 shocks occurred appears to be a zone where there had been extensive pre-late Cretaceous shearing. Thus, a possibly diagnostic feature of this seismic area is that the most damaging earthquakes are occurring along a major shear zone that is well-oriented to the regional direction of maximum horizontal compression.

CRUSTAL DEFORMATION

How then do we identify possible sites of future large and damaging intraplate earthquakes? Although there has been considerable discussion of "weak zones" in the crust which localize intraplate seismicity (see, for example, Sykes, 1978), it is difficult to prescribe the responsible physical mechanisms for crustal weakness (see discussion by Zoback and Zoback, 1981). One possible mechanism for localizing major intraplate earthquakes along specific faults is based on a hypothesis previously discussed by N. Ratcliffe and others. Namely, that there are pre-existing ductile shear zones in the lower crust which concentrate deformation and thus concentrate stresses in the upper crust. Laboratory rock deformation evidence suggest that such zones could exist in the lower crust. As shown in Figure 4, theoretical studies clearly show that such zones would cause localized areas of high stress in the brittle crust (the example shown is for the strike-slip faulting but the same is true for reverse or normal faulting).

We have recently undertaken a study of historic triangulation data in the Charleston and New Madrid areas in an attempt to determine if significant strain can be detected due to localized lower crustal deformation. Figures 5 and 6 show the location of historic triangulation lines in the Charleston and New Madrid areas. Unfortunately, we have not been able to test the strain localization hypothesis with these data because in neither area have there been repeat surveys of lines in the actual seismic areas. However, the existing data do provide a sufficiently long data set for future measurements to test the strain localization concept. Recently developed geodetic techniques using Global Positioning System satellites would make such work quite efficient. If such a research program was successful, it could be used to explore for strain localization along intraplate faults which could potentially produce damaging earthquakes in the future.

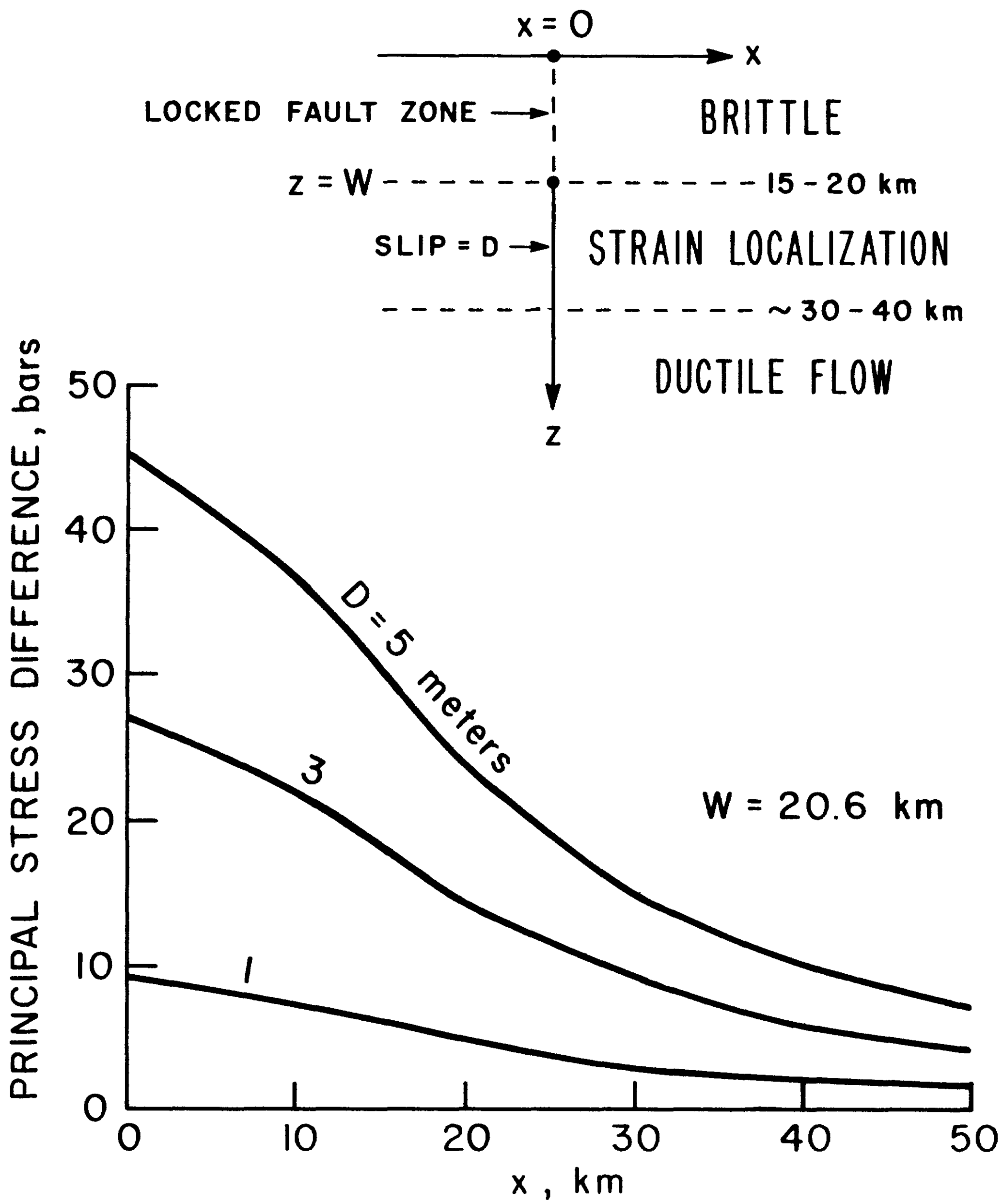

Figure 4.--Conceptual model of strain localization in lower crust causing faulting in upper crust. Model results show stress at the surface as a function of distance from the fault for various amounts of aseismic strike slip motion at depths greater than 20.6 km.

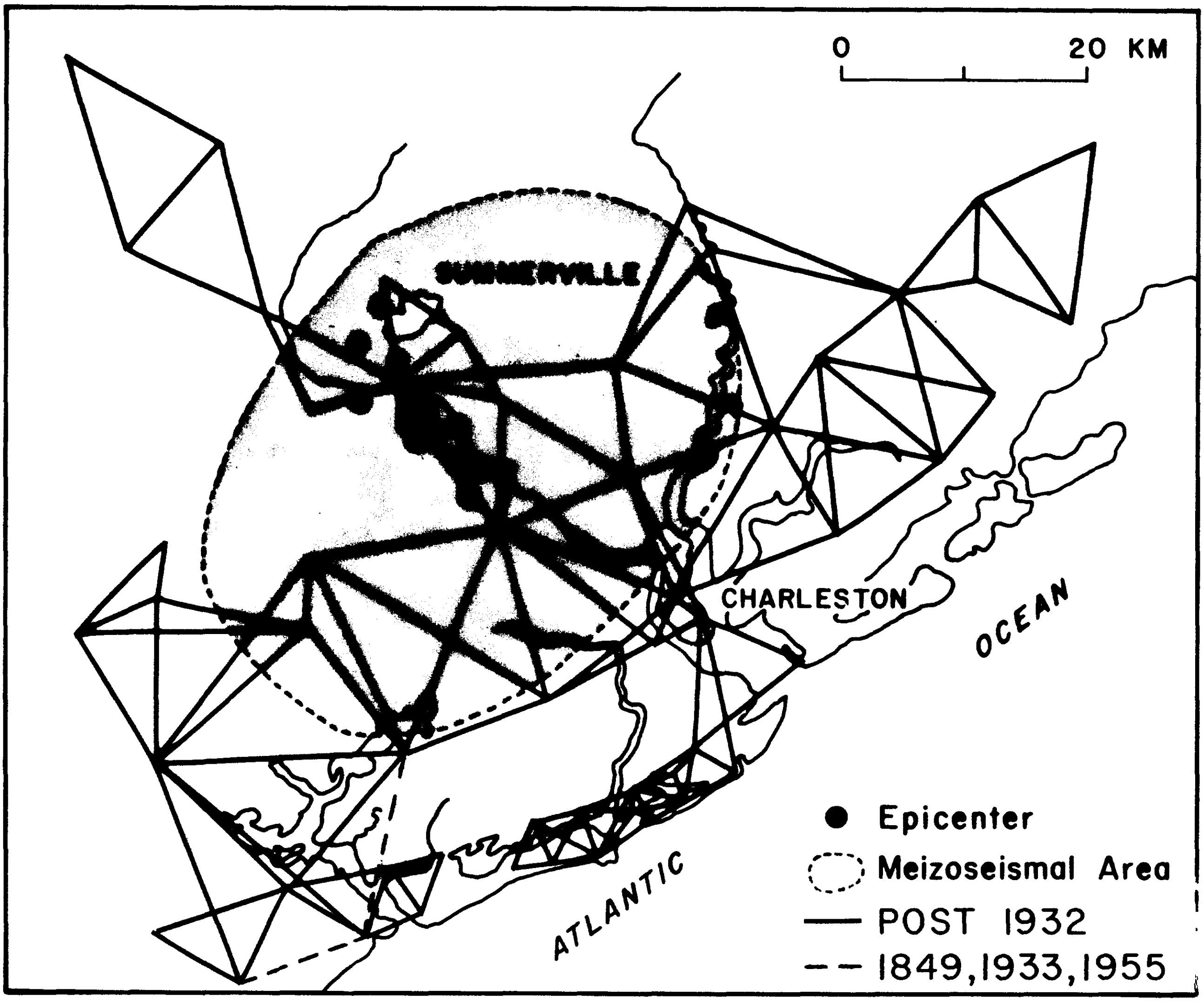

Figure 5.--Historic triangulation lines in the Charleston area.

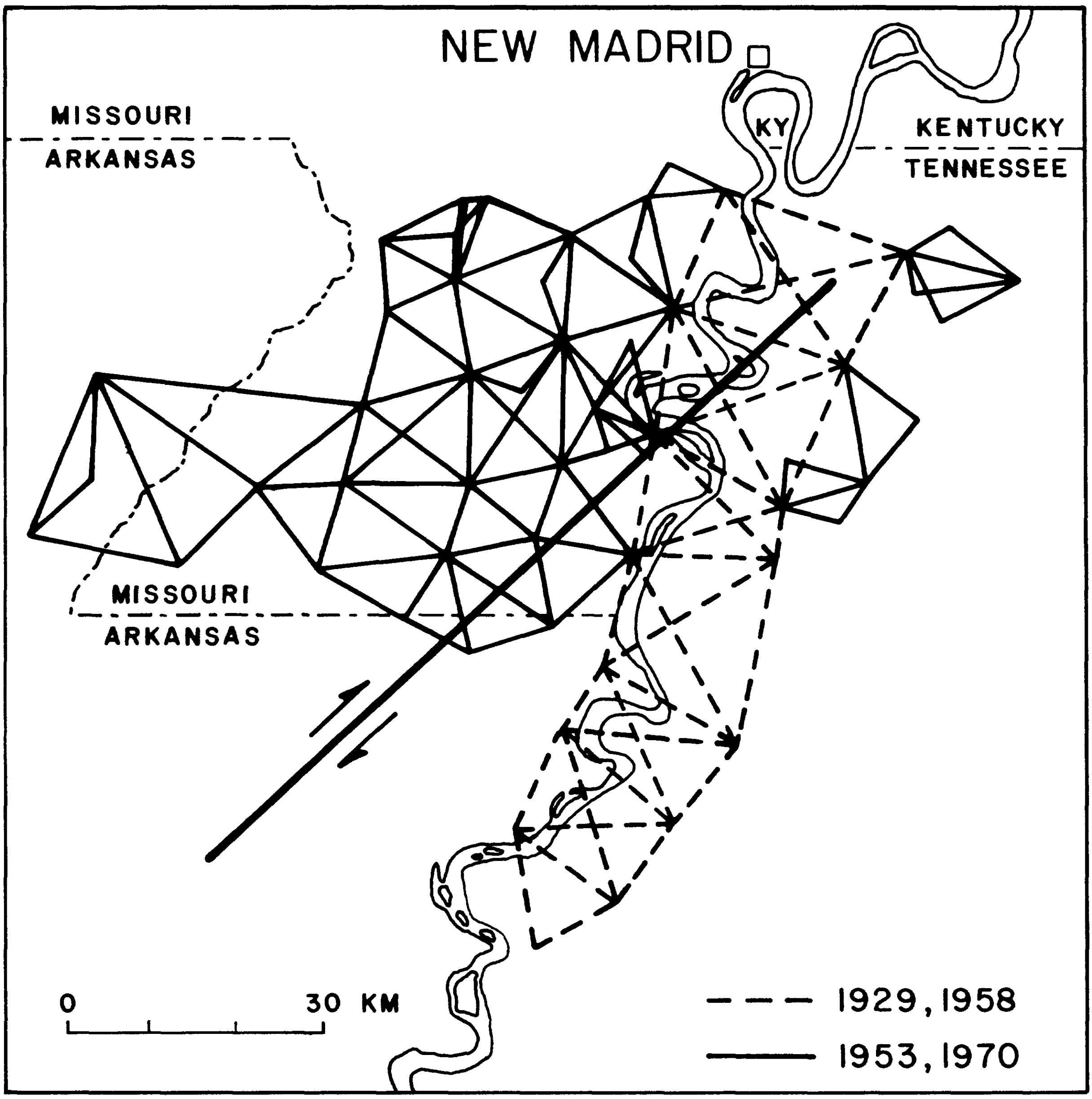

Figure 6.--Location of historic triangulation lines in the New Madrid area.

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THE ROLE OF GEOLOGIC INVESTIGATIONS IN STUDIES OF EASTERN SEISMICITY: PERSPECTIVE FROM THE U.S. GEOLOGICAL SURVEY'S CHARLESTON PROJECT

by

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INTRODUCTION

Geologic investigations provide critical information that is required for formulating seismotectonic models of the Eastern United States and that is unattainable from other types of investigations. Perhaps the single greatest and unique contribution of geologic studies to earthquake research is a knowledge of the timing and frequency of tectonic events and pre-modern seismic events. Geologic investigations contribute significantly to: the definition of tectonic and seismotectonic provinces; the recognition of specific structures, their tectonic affinities, and their movement histories, the documentation of broad-scale Cenozoic crustal deformation; and the recognition of individual historic and prehistoric seismic events as recorded in near-surface materials. Our still-evolving understanding of Eastern seismicity has advanced significantly in multidisciplinary programs where geologic studies were integrated with geophysical and seismologic studies.

USGS CHARLESTON PROJECT: GEOLOGIC STUDIES

The Beginning

Prompted by an increasing concern with the seismic hazard to critical facilities in the East, several federal agencies, as well as other institutions, initiated major efforts during the 1970's to understand the origin(s) of Eastern seismicity. One natural target for these investigations was the Charleston, South Carolina, area, which had experienced an MM intensity X earthquake in 1886 and which continues to experience seismicity.

However, the geologic (and geophysical) data base for the Atlantic Coastal Plain in the Charleston area was limited in quantity and type of information. The existing geologic map for the area was 40 years old and was compiled at a small scale (1:500,000) that did not provide the detail necessary for local structural and stratigraphic studies. Work on the surface and near-surface geology of the Charleston Area during the 1960's and earlier was limited primarily to studies of the thin Pleistocene section. Published studies of the subsurface Coastal Plain sediments consisted principally of short discussions in ground-water studies, which typically lacked paleontologic analyses. As late as 1974, only one drill hole (the poorly documented Summerville oil test drilled in 1920 or 1921) had penetrated the base of the Coastal Plain section within 100 km of Charleston; hence, the pre-Cretaceous "basement" geology of the Charleston earthquake zone was virtually unexplored.

The initial phase of Charleston research consisted of a major research effort to expand our limited knowledge of the basic geology of the earthquake zone. Only after a geologic (and geophysical and seismologic) data base was constructed, has it been possible to generate cogent seismotectonic models that involve specific structures.

Methods and Principal Results

Geologic investigations by the USGS in the Charleston area since 1974 have consisted of field mapping and drill-hole investigations of pre-Cretaceous rocks and Cretaceous, Tertiary, and Quaternary sediments. Three deep drill holes at Clubhouse Crossroads, located northwest of Charleston, provide most of the available geologic record of pre-Cretaceous rocks in eastern South Carolina. At Clubhouse Crossroads, a sequence of Lower Jurassic basalt flows and underlying lower Mesozoic sedimentary red beds occurs beneath the Coastal Plain sequence. Petrologic, stratigraphic, geochemical, radiometric, and paleomagnetic studies of the basalt and red-bed section established the ages of these units and their similarities to geologic sections in other early Mesozoic rift basins in the Eastern United States. Several models for Charleston seismicity involve Cretaceous and Cenozoic reactivation of zones of early Mesozoic normal faulting and the possible hereditary relationships among early Cesozoic faults and Paleozoic faults.

Because of drilling problems, pre-Mesozoic rocks could not be reached at Clubhouse Crossroads. Hence, our geologic knowledge of the Charleston basement and its pre-Mesozoic tectonic history remains verv limited. Uetrital crystalline-rock fragments in coarse-grained lower Mesozoic red beds represent the only available samples of basement rocks in the Charleston area. The fragments consist of granitic and basaltic rocks as well as brecciated and mylonitic rocks that suggest the presence of ancient fault zones in continental crust in the Charleston area.

The Cretaceous and Cenozoic geologic history of the Charleston area is reasonably well known from litho- and biostratigraphic studies of the continuously cored Cretaceous and Tertiary section in Clubhouse Crossroads #1 and field studies of Pleistocene sediments. At Clubhouse Crossroads, the Upper Cretaceous section consists of about 500 m of deltaic sediments overlain bY a total of 250 m of deltaic Paleocene sediments, Eocene and Oligocene carbonate sediments, and Pleistocene marine and fluvial sediments. The thicknesses and elevations of the various Coastal Plain units, when studied regionally, provide a basis for describing the magnitude of Cretaceous and Cenozoic crustal warping in South Carolina. As described below, knowledge of the stratigraphy of the Coastal Plain sediments is of importance in other phases of Charleston project work.

Uses of Geological Data In Multidisciplinary Studies

In addition to interpretations of tectonics that result directly from geologic research, the geologic data that are generated by this research have other important applications in integrated, multidisciplinary studies of Eastern seismicity. These applications fall into two main categories: the geologic calibration of geophysical surveys, and the generation of "groundtruth" constraints for seismotectonic models produced by other tvpes of investigations.

The calibration of geophysical surveys principally involves the addition of chrono- and lithostratigraphy to seismic stratigraphy. With the available drill-hole data, reflecting and refracting horizons in the Charleston area can be correlated specifically with Coastal Plain horizons, the Jurassic basalt, the red-bed section, and crystalline basement rather than discussed in general terms. Therefore, integration of geophysical and drill-hole data provides a powerful method for the mapping of major upper crustal units and the recognition of specific structures.

Where specific structures are identified, the existing chronostratigraphic information provides a good basis for understanding the movement history of the fault or flexure. For example, the Cooke Fault, located along the western edge of the meizoseismal zone of the 1886 earthquake, is interpreted from seismic-reflection surveys and drill-hole stratigraphic data as a growth fault that deforms reflectors of pre-Jurassic to Eocene age. Non-stratigraphic data for the calibration of geophysical surveys are also available from drill holes. That is, acoustic velocity, density, and other physical properties of subsurface materials are derived from studies of cores and from drill-hole geophysical logs.

Geologic knowledge of the types and histories of major structures in the Charleston area serves to constrain seismotectonic models of Eastern seismicity on local and regional scales. Geologic studies of the tectonic affinities and movement histories of structures in the Charleston earthquake zone have been combined with geophysical data and with location data for historic and modern earthquakes to formulate local models for the genesis of Charleston seismicity (models are discussed elsewhere in this volume). On the larger scale, our now-expanded knowledge of the seismically active Charleston area, which was developed in the context of regional studies of Eastern tectonics, is a contribution to the formulation of regional seismotectonic models. Ultimately, any general seismotectonic model for Eastern seismicity must be geologic in nature; that is, it must derive from, and be compatible with, our knowledge of the tectonic history- and structural fabric of the East.

Future Work

In the following paragraphs, three categories of new or continuing geologic studies in the greater Charleston area are described. These categories of additional work address poorly understood and important aspects of the seismicity and tectonics of the Charleston area. A better understanding of these aspects will provide a basis for critical evaluation of individual models for Charleston-area seismicity. In addition, an improved understanding of the recurrence interval for large earthquakes in the Charleston area may be achieved. Given that some uncertainties exist in the deterministic models for Charleston seismicity, knowledge of the recurrence interval for 1886-type events near Charleston is important for probabilistic assessment of seismic risk in the engineering design of critical facilities.

These three categories are:

(1) Investigation of liquefaction and related ground-shaking

Sand blows and related features are known to have accompanied the 1886 Charleston earthquake but little exploration of these features has been done in recent years. Because the near-surface geology of the Charleston area is now well known (including the ages of Quaternary deposits) and because a brief reconnaissance has uncovered some sand-blows, the potential clearly exists for studying these features in detail. A possible reward of such investigations would be the discovery of evidence for major pre-1886 events; knowledge of these older seismic events would address the question of recurrence intervals for large earthquakes in the Charleston area. In addition, added knowledge of 1886 sand blows and related phenomena may refine our understanding of the location of the 1886 earthquake.

(2) Geologic investigations of the Cenozoic movement history of reverse faults.

High-angle reverse faults that deform Tertiary sediments in the Charleston area have been interpreted from seismic-reflection surveys. These faults are integral parts of several seismotectonic models of Charleston seismicity. The effect of these faults on the Tertiary sedimentary section can be explored further by drilling paired 300-m drill holes along the seismic-reflection surveys near the faults. Additionally, if suitable target areas were identified, trenching of sediments in fault zones could provide valuable information on Quaternary fault movements.

(3) Deep drilling to test seismotectonic models of Charleston-area seismicity.

Although costly, drilling to depths of one or two kilometers is a direct method of investigating the nature and distribution of lower Mesozoic rocks, pre-Mesozoic rocks, and major structures in the Charleston area. Therefore, drill holes to these depths can be used to test critical or equivocal aspects of proposed seismotectonic models. In addition, holes drilled to these depths provide an opportunity to investigate the stress field in rigid rocks below the Coastal Plain sediments.

GEOPHYSICAL TECTONIC STUDIES OF THE UNITED STATES ATLANTIC COASTAL PLAIN AND CONTINENTAL MARGIN

by

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INTRODUCTION

The crustal structure of the United States east of the Appalachian Mountains was formed over the past 500 m.y. as the result of at least three Paleozoic collision episodes (orogenies) (Rodgers, 1970) and a Late Triassic-Early Jurassic rifting event. The initiation of sea floor spreading in the Jurassic was followed by the development of a series of marginal sedimentary basins (Sheridan, 1974; Folger et al., 1979). This sequence of tectonic events resulted in both the superposition and juxtaposition of different lithotectonic terranes with differing geological, geophysical, and tectonic signatures (Williams, 1978; Hatcher, 1978; Williams and Hatcher, 1982).

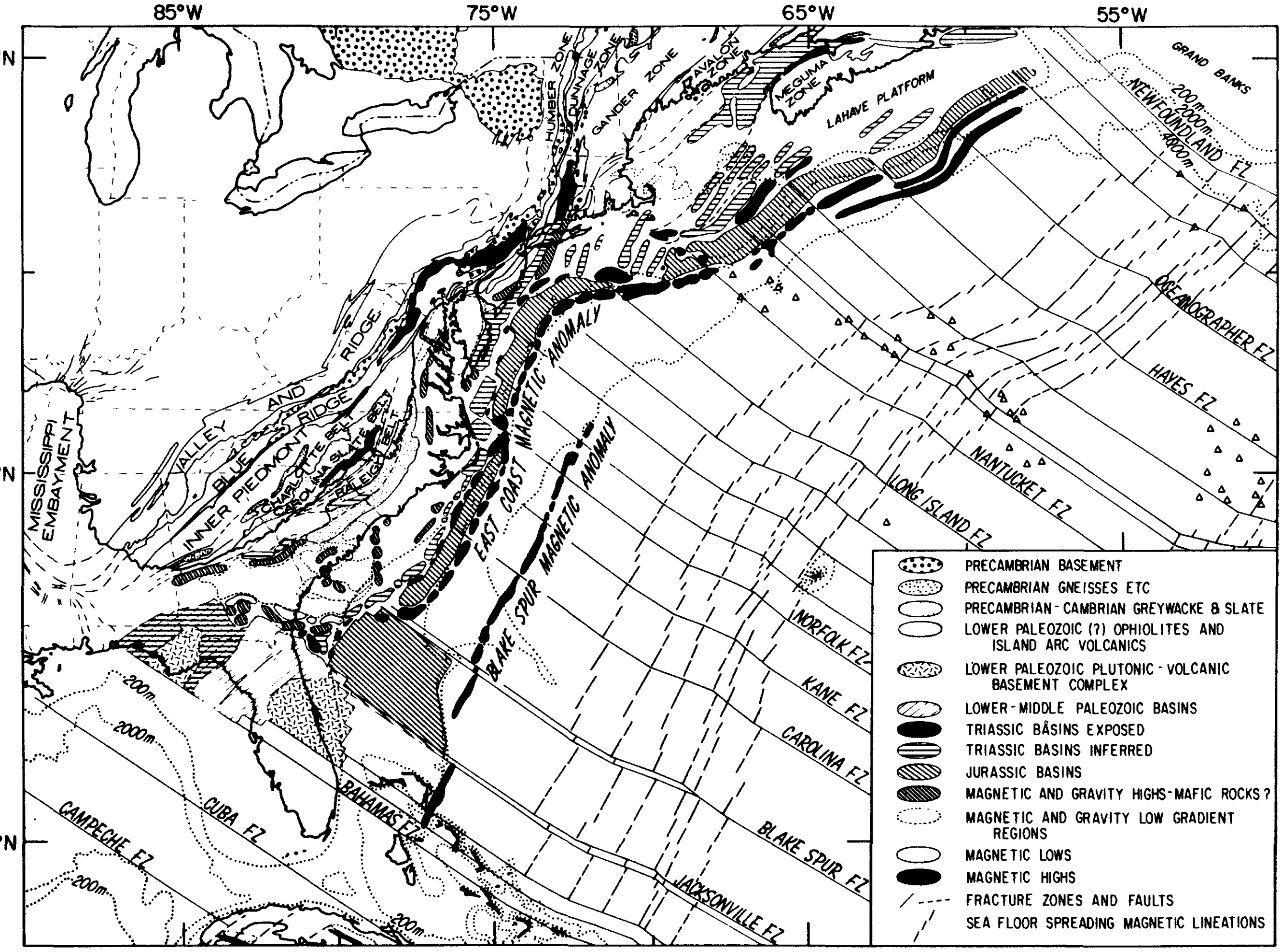
To unravel the tectonic history of the region it is necessary to identify the individual lithotectonic terranes (such as old island arc belts, oceanic crust and ophiolite belts, continental margin sedimentary basins, and interior sedimentary basins), the structural features that bound and cross these terranes (such as normal faults, thrust planes, and grabens), and the igneous features that have modified these terranes (such as dikes, plutons, batholiths, and other suites of rocks), and the absolute (or at least relative) ages of formation and tectonic significance of the features.

Essential three-dimensional geologic and structural information is obtained by field mapping and by analyses of drill-hole data integrated with geophysical studies using magnetic, gravity, electromagnetic, seismic-reflection, and seismic-refraction data. Rock age dating, stratigraphic studies, palinspastic, paleoenvironment, plate-tectonic and paleomagnetic reconstructions, and kinematic model studies provide the basic framework in which tectonic events can be isolated and "stripped off" back through time. For our studies of the Atlantic Coastal Plain and continental margin summarized here, we have relied primarily on the analyses of magnetic and gravity signatures and plate tectonic reconstructions of the Jurassic opening of the Atlantic, Late-Triassic rifting, and late Paleozoic collision (Alleghenian orogeny).

ATLANTIC MARGIN STRUCTURES

Geophysical studies of the Atlantic continental margin (Sheridan, 1974; Folger et al., 1979; Klitgord and Behrendt, 1979; Grow et al., 1979) and Coastal Plain (Pavlides et al., 1974; Rankin (Editor), 1977; Hatcher et al., 1977; Daniels and Zietz, 1978; Long, 1979; Cook et al., 1979, 1981; Hatcher and Zietz, 1980; Gohn (Editor), 1983) have outlined many of the primary structures (Figure 1). A series of Jurassic marginal rift basins line the edge of the continental block. A narrow, block-faulted basement hinge zone separates crystalline rock with a thin sediment cover (<3 km) from the thick sediment fill (>10 km) in the marginal basins that underlie the Continental Shelf, Slope, and Rise. Lateral offsets in this basement hinge zone controlled sediment-deposition patterns along the margin and correlate with major oceanic fracture zones mapped in oceanic crust to the east (Klitgord and Behrendt, 1979). Landward of the basement hinge zone, numerous faults have been inferred from magnetic data (Hatcher et al., 1977; Mixon and Newell, 1977; Popenoe and Zietz, 1977; Simpson et al., 1980; Klitgord et al., 1983; Daniels et al., 1983) and buried rift or graben structures have been identified with magnetic, gravity, seismic-reflection, and drill-hole data (Marine and Siple, 1974; Rankin (editor), 1977; Klitgord and Behrendt, 1979; Long, 1979; Costain et al., 1982; Gohn (editor), 1983).

The correlation of magnetic data with some of these faults, grabens, and other structures is shown in Figure 2. Narrow, linear magnetic lows are associated with mylonite zones and other cataclastic rocks that mark the surface expression of faults (Hatcher et al., 1977). Many of these zones are associated with large thrust faults mapped using seismic-reflection data (Cook et al., 1979, 1981). Triassic(?) grabens usually have large associated magnetic lows (Sumner, 1977; Daniels and Zietz, 1978; Klitgord and Behrendt,



KLITGORD & SCHOUTEN 1980

Figure 1.--Tectonic structures in the western Atlantic Ocean and on the North American continental margin. Paleozoic lithotectonic features in the Appalachians are from Williams (1978), Late Triassic-Early Jurassic rifting, marginal basins, and Jurassic and Cretaceous fracture zones and sea-floor spreading magnetic lineations are from Klitgord and Behrendt (1979) and Klitgord and Schouten (1982).

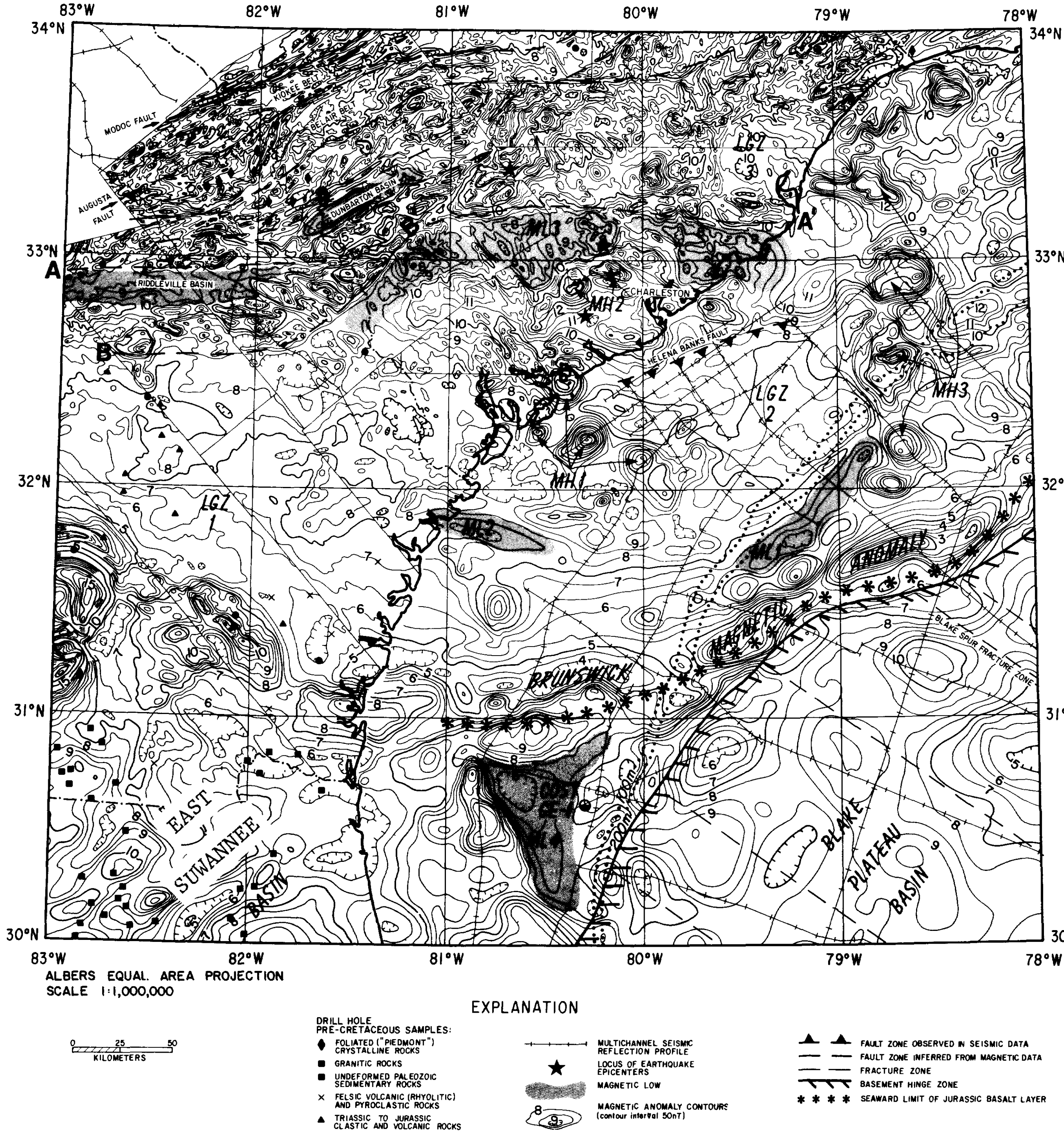


Figure 2.--Magnetic-anomaly map of the Georgia and South Carolina Coastal Plain and continental margin (from Klitgord et al., 1983). LGZ refers to a magnetic and gravity low-gradient zone, ML refers to a narrow magnetic low, and MH refers to a magnetic high. Charleston area earthquake epicentral regions (not individual epicenters) are indicated with stars.

1979) although they are sometimes hard to distinguish from elongate granitic bodies. Other geologic features such as granitic and mafic plutons, dikes, and many metamorphic or plutonic terranes also have distinctive magnetic and gravity signatures (Pavlides et al., 1974; Daniels and Zietz, 1978; Hatcher and Zietz, 1980) by which they can be recognized and mapped both where exposed and beneath the Coastal Plain. For instance, similar broad zones of low-gradient magnetic and gravity field (presumably granitic batholiths) underlie the Charleston region and also the Salisbury embayment (Klitgord et al., 1983). Both zones straddle the late Paleozoic collision boundary and are rimmed by grabens and faults.

PAST ATLANTIC MARGIN TECTONICS

Late Paleozoic collision of Gondwanaland (Africa and South American plus other continents) with Laurasia (North American and Asia) sutured together the megacontinent of Pangaea. The event included true collision in the southern Appalachians, with large scale thrusting (in the Piedmont) and folding (in the Valley and Ridge) and right-lateral shear in the northern Appalachians (in Southeastern New England, Gulf of Maine, and Bay of Fundy) connecting the southern Appalachians with the Urals (Rodgers, 1970; Arthaud and Matte, 1977; Hatcher, 1978; Cook et al., 1979, 1981). Assuming that the reconstructed Jurassic closure of the Atlantic provides an adequate paleogeography for Pangaea at the end of the late Paleozoic (Figure 3) (Klitgord and Schouten, 1982), then the lithotectonic features of both Africa and North America can be examined for other possible transform or shear zones, suture zones, and anomalous terranes (Lefort and Van der Voo, 1981). A suture zone-magmatic arc complex (the Brunswick terrane, Figure 4) beneath the Coastal Plain has been postulated by Williams and Hatcher (1982) and corresponds to a (a) the low-gradient magnetic and gravity zones of Klitgord et al. (1983) beneath the Salisbury Embayment and in the Charleston region and (b) the South Georgia main rift basin of Daniels et al. (1983). The boundaries between these magmatic arc regions and thin-sheet thrusting in the Avalon(?) terrane (the zone which includes the eastern Piedmont and Carolina Slate Belt in the terrane model of Williams and Hatcher, (1982) although correlation of this zone with the Avalon zone to the north is not certain (Secor et al. 1983)) may have been trench-trench transform faults during the late Paleozoic (Lefort and Van der Voo, 1981).

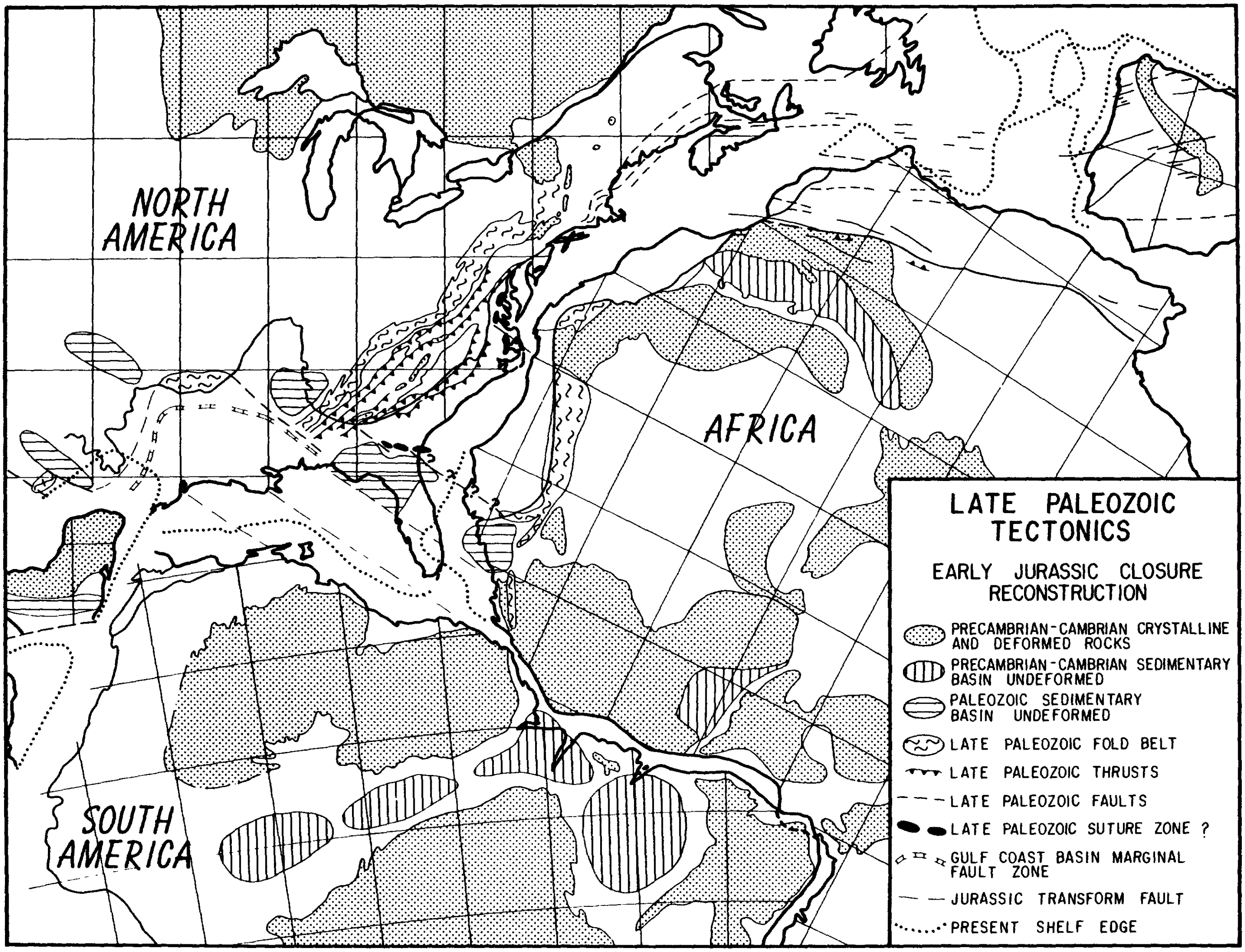


Figure 3.--Late Paleozoic tectonic features around the Atlantic. The reconstruction positions of the continents are from Klitgord and Schouten (1982) and are the same as at the initiation of rifting in the Early Jurassic.

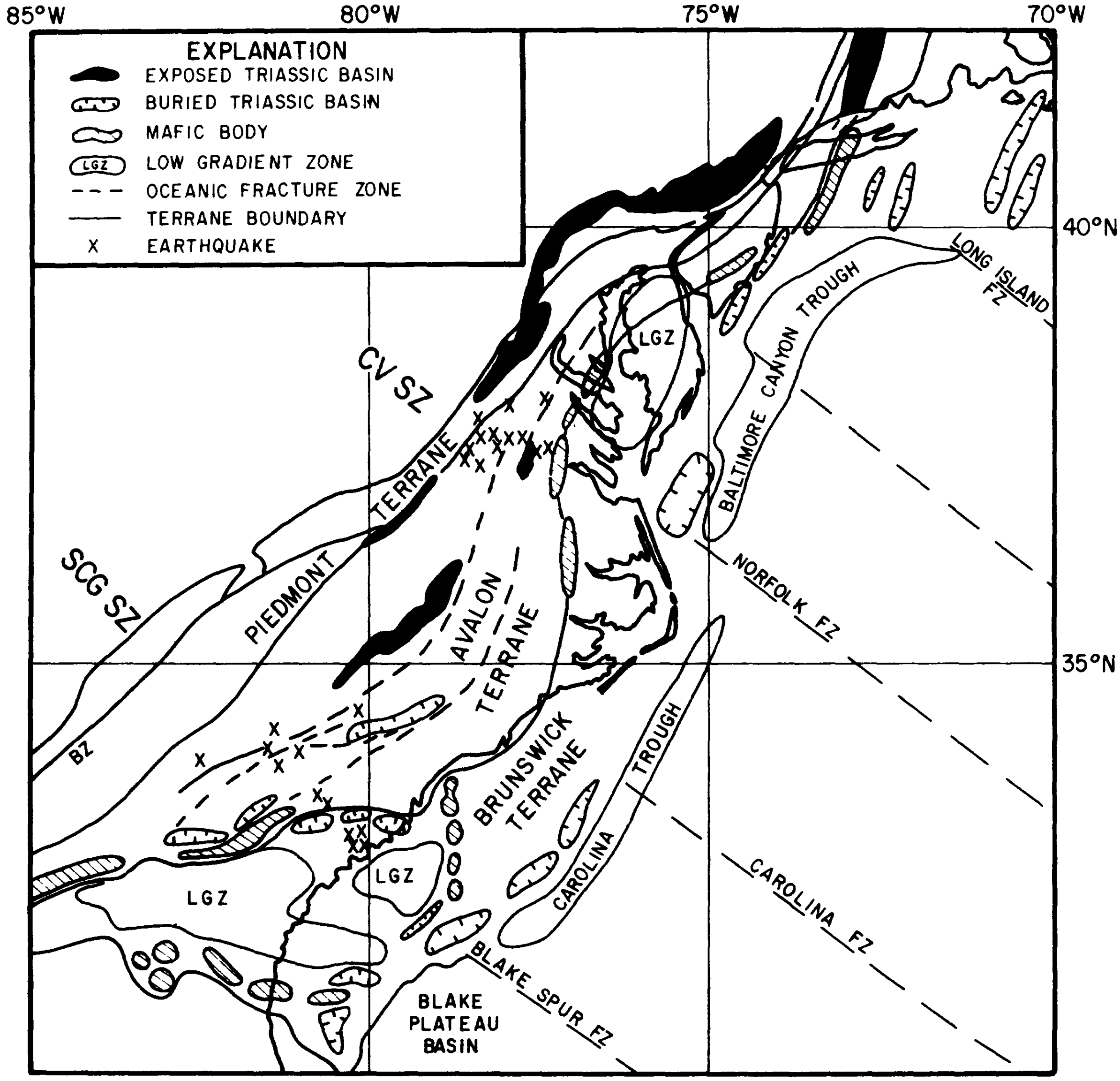


Figure 4.--Schematic map of the Eastern United States including the continental margin showing the relationship between seismic zones and major tectonic structures and terranes. CVSZ=Central Virginia seismic zones, SCGSZ=South Carolina-Georgia seismic zone, LGZ= Low gradient zone, BZ= Brevard zone, and FZ= Fracture zone. Only Earthquakes in the CVSZ and SCGSZ (Bollinger, 1973; Seeber and Armbruster, 1981) are indicated.

Late Triassic rifting between North America and Africa produced a series of narrow grabens between the two continents (Manspeizer, 1982) but did not actually break them apart. Offshore structures indicate that there are probably two parallel sets of grabens (Klitgord and Behrendt, 1979; Klitgord et al., 1983) similar to the present East African Rift System. Diabase intrusion was associated with this rifting but there was not the massive amounts which would have been associated with a significant amount of plate separation. COCORP data indicate that some (but not all) of the late Paleozoic thrust faults were reactivated by the rifting (Cook et al., 1981).

Separation of North America and Africa in the Early Jurassic was localized along the eastern set of rift grabens (Klitgord et al., 1983) with the pervasive intrusion of igneous dikes into older crust (rift-stage crust) giving way to the generation of oceanic crust as sea-floor spreading was initiated. The accumulation of sedimentary rock on the cooling and subsiding rift-stage crust and adjacent oceanic crust formed the marginal sedimentary basins beneath the present Continental Shelf. Initial offsets in the eastern rift zone and basement hinge zone of these marginal basins probably resulted from older zones of weakness in the crust which failed when the continents started to pull apart (Sykes, 1978). These horizontal offsets in the rift zone persisted as transform fault offsets in the spreading center system, generating a fracture zone trace away from the margin. Thus, the large offset fracture zones serve as markers which point towards older major zones of weakness landward of the marginal basins; these fracture zones should not extend landward of the basement hinge zone because active transform faulting occurred only seaward of the hinge zone.

PRESENT ATLANTIC MARGIN TECTONICS

Seismicity patterns on the Eastern United States margin (Bollinger, 1973; Sykes, 1978; Seeber and Armbruster, 1981; Talwani, 1982; Gohn (Editor), 1983) indicate a few local zones of concentrated activity superimposed on a broad regional level of seismic activity. While there is still uncertainty in the source location for the earthquakes (e.g. Sykes, 1978; Behrendt et al., 1981; Seeber and Armbruster, 1981; Talwani, 1982) or the orientation and origin of the regional compressive stress (Zoback and Zoback, 1980), the reactivation of older faults or thrust planes may be important (Seeber and Armbruster, 1981; Wentworth and Mergner-Keefer, 1982). The direct association of seismicity with late Paleozoic thrust planes is considered reasonable by some researchers (Seeber and Armbruster, 1981; Talwani, 1982) but it is not well documented. Only some of the Triassic grabens have seismic activity around them while others do not. It is important to note that there is almost no reported seismic activity associated with the Jurassic marginal basins, sites of the most recent major block-faulting crustal tectonics in the Eastern United States.

Two of the most important seismic zones off-axis from the main Appalachian seismic trend, the South Carolina-Georgia seismic zone (SCGSZ) and the central Virginia seismic zone (CVSZ) (Bollinger, 1973), lie near the junction of major late Paleozoic and Triassic tectonic structures and just landward of major offsets in the Jurassic marginal basin system (Figure 4). The SCGSZ lies along the boundary which separates the Brunswick terrane (South Georgia rift main basin of Daniels et al. (1983) and low-gradient zones of Klitgord et al. (1983)) and the Avalon(?) terrane of Williams and Hatcher (1982) with a large concentration of seismicity occuring near the Jedburg Triassic basin (Hamilton et al., 1983). The CVSZ is located along the boundary between Avalon(?) terrane and the Salisbury Embayment which is underlain by Brunswick type crust. Here the seismicity is concentrated near the intersection of this boundary with the Richmond Triassic basin. Thus, these two seismic zones appear to be located near the major terrane boundary that separates an old magmatic arc belt (Brunswick terrane) from a belt of thin sheet thrusting (Avalon terrane) and near structures later generated by early Mesozoic extension. The seismic zones also occur directly landward of major oceanic fracture zones that offset the continental edge; the Blake Spur fracture zone that separates the Blake Plateau basin from the Carolina trough, and the Norfolk fracture zone that separates the Carolina trough from the Baltimore Canyon trough. Although these two fracture zones are located seaward of the basement hinge zone, they point towards the two seismic zones, giving the false impression that the fracture zones continue landward of the hinge zone.

FUTURE RESEARCH

Research should be pursued geologic and in geophysical mapping of crustal structures beneath the Coastal Plain and inner Continental Shelf landward of the basement hinge zone. The use of magnetic and gravity data in conjunction with seismic-reflection data for such mapping should be encouraged; this should include the acquisition of new aeromagnetic and gravity data in regions of poor data quality and the acquisition of additional seismic reflection and refraction data across the Coastal Plain and inner shelf, particularly across the major terrane boundaries. The areal extent and geometry of thrust faulting noted by COCORP needs to be determined, and the relationship between these large thrust sheets and the block-faulted basement hinge zone along the western edge of the marginal basins should be resolved. Why are there almost no reported earthquakes along or seaward of the basement hinge zone? These regions needs to be monitered to establish if the absence is real or results from a sampling bias; and to provide more complete azimuthal coverage for investigating earthquakes near the coast. What is the relationship of these thrust sheets to the broad magnetic and gravity low gradient zones (Charleston region and Salisbury embayment)? Seismic refraction and seismic wave propagation studies in addition to the deep seismic reflection profiles need to be undertaken to constrain the velocity structure of the crust for modeling. Plate tectonic, paleomagnetic, paleoenvironment, and palinspastic reconstructions and kinematic modelling should be actively used to remove (backstrip) the effects of various tectonic events through time.

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ROLE OF GEOLOGICAL AND GEOPHYSICAL DATA IN EVALUATION OF CRITICAL HYPOTHESES-- "THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE"

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INTRODUCTION

Few events present so frustrating an enigma as does the occurrence of the 1886 Charleston, South Carolina, earthquake. As a demonstration of potential seismic risk, the Charleston earthquake is one of a few scattered exceptions in the Eastern United States to a relatively low level of observed seismicity. This event is a staunch reminder that a significantly damaging earthquake can occur. A plethora of hypotheses have been proposed as solutions to the Charleston enigma, with many attributing a uniqueness to the Charleston area. However, none have to date proven sufficiently convincingly so as to achieve general acceptance. After many studies, the Charleston area has not yielded data showing it to be unique in any significant way, except in demonstrated seismicity. Existing hypotheses often oversimplify the tectonic mechanism by attempting to tie the earthquake to singular quantities such as a simple fault, the intersection of trends, Mesozoic basins, or some other feature observed in geological or geophysical data. Instead, perhaps, the fundamental problem that needs to be addressed is the manner in which accumulated stress is released in the crust of the Eastern United States. The riddle of Charleston will probably not be solved until this fundamental problem is addressed. In order to achieve a solution, two research projects are suggested. First, all available data and new data must be collected and examined. A common base or grid spacing should be chosen to facilitate multiple data-base analysis. Data bases not always grouped with geological and geophysical data such as LANDSAT multi-channel data must be included and examined simultaneously with the geophysical data. Second, the material properties of the earth's crust as a function of depth, temperature, composition, and stress must be better understood.

A large and potentially damaging earthquake occurs when a major portion of the earth's rigid crust, a thickness of 10 to 20 km, fails along one or more planes. The earthquake vibrations are a transient and often damaging manifestation of failure, while the faults are a permanent manifestation of this failure. Both occur in response to an applied stress. In the study of Eastern United States seismic risk the challenge is to relate recent faulting or seismicity to the applied stresses and to the physical conditions conducive to failure. Physical conditions conducive to failure include inhomogeneities in composition, thickness, and mechanical properties. Also, the applied stresses are in part inhomogeneous and may be derived from external or internal sources. Geological and geophysical data can define the major inhomogeneities, but the mechanical properties are poorly understood and the origin of stresses remains largely in the realm of speculation. A successful hypothesis for Eastern United States earthquakes would ultimately have to satisfy these known and unknown factors.

ROLE OF GEOLOGICAL AND GEOPHYSICAL DATA

Today (1983), the unknowns in the problem of Eastern United States seismicity are too many to permit a simple test evaluation of any one hypothesis. Because the fundamental problem is one of the mechanical properties and the source of stresses of the crust, no single measurement available today could conceivably provide a decisive key to the answer. Each new piece of data may, however, contribute in an important way to the solution of the puzzle, even contribute though many critical pieces may be missing at this time.

Potential Data: Although structural interpretations based on potential data are non-unique, magnetic and gravity data will probably dominate as a source of information on the physical properties of the crust. Density and susceptibility contrasts relate to compositional variations which can be constrained by discontinuities more precisely derived from other data such as seismic reflection profiles. Structural interpretations will eventually require gravity and magnetic values spaced no more than 0.5 to 1.0 km apart.

Such data would be appropriate for both regional analysis and local site specific analysis.

Reflection and Refraction Seismic Data: Reflection data provide a unique image of sharp contrasts or discontinuities in the velocity structure of the upper crust. Some hypotheses assign the Charleston earthquake to a convenient contrast (interpreted as a fault), but such assignments are not always compatible with the seismicity data. Usually, deeper structures and the crustal thickness must be obtained from refraction data. Reliable shear and compressional wave velocity measurements will be required for definition of mechanical properties. An expanded and improved seismic net could significantly enhance the availability of such data for analysis.

Stress Measurements: Measurements of stress at depths no greater than a kilometer may be difficult to relate directly to the occurrence of large earthquakes because topography, near-surface weathering, residual stresses from uplift, and geologic structures may perturb the stress field. Also, crustal inhomogeneities at depth may exist and perturb the stress at depth. One should not be surprised if most near-surface measurements indicate horizontal compression, since a tensional stress would encourage weathering along joints and render the rock inappropriate for many types of stress measurement. Unfortunately, drill holes are not yet deep enough to sample the stress fields at hypocentral depths of 10 to 15 km. Hence, the existing high quality stress measurements made near the surface can serve only as a boundary condition for interpretation of the stress field in the crust.

Earthquake Studies: Aftershock locations and focal mechanisms provide direct evidence of the geometry of the planes of failure or the volume of stress relaxation. Results of studies in Eastern United States seismic zones, Charleston and New Madrid, are similar to results from detailed studies of the distribution of aftershocks in major shear zones, like the San Andreas, in that the aftershocks of a large event fall along multiple subparallel faults, often with movement as well on connecting transverse fault planes. The lack of evidence for surface displacements in the east could be explained by a distribution of small displacements along many near-surface faults. Complementary sets of fault planes or en echelon failure may be a more characteristic geometry for releasing accumulated stress in a volume of crust characterized by inhomogeneity of the driving stress and/or the inelastic material properties. Alternatively, faults and seismicity in the crust may be a spatially transient phenomena which do not accumulate observable displacements. The degree of crustal inhomogeneities could determine the ellipticity of the aftershock zone and separation of subparallel fault planes. More detailed seismic monitoring could help define the active volume. Seismic network data analysis which to date has been limited in South Carolina could be useful in defining the velocity structure of the crust.

Fault Studies: The geometry of many well-mapped fault systems complement aftershock studies. The Belair fault system near Augusta, Georgia, is a sequence of en echelon displacements with significant displacements confined to the central portions of the zone. On such faults the movement is typically transient in time as well as limited in dimension, indicating inhomogeneous and time varying stress conditions. The degree of crustal distortion as indicated by an opensity for faulting, such as in the New Madrid area, provides evidence for stress and structural conditions conducive to the repeated generation of earthquakes. Failure along existing faults (of different geologic ages) is not consistent with either the observed distribution of faults in the Eastern United States, including the multiplicity of faults in the Reelfoot rift, or the complexity of crustal deformation as evidenced by multiple faults in major strike slip fault zones. The concept of a fault being a permanent zone of weakness which responds to distant or homogeneous sources of stress may need to be re-examined.

Statistical Studies: The determination of recursion relations, saturation at large magnitudes, and the influence of aftershocks has been so ambiguous that risk estimates based on statistical data are now being placed in a probabilistic framework constrained by expert opinion. At lower magnitude levels (2.0 to 4.5) the background seismicity satisfies the recursion relations when such studies use homogeneous and carefully controlled data sets. However, the longterm stability of the relations and their applicability at higher magnitudes has been questioned, particularly for the Charleston seismicity. The rate of occurrence of events from 1886 to today in the Charleston area satisfies statistical relations for aftershocks with no significant indication of approaching a background level of seismicity Charleston may be a type example of conditions where the stress applied, the cumulative strain, and geometry of crustal strength, have combined to cause an isolated foreshock-main event aftershock sequence. The hypothesis that observed seismicity in the Eastern United States consists only of similar sequences is not precluded by the statistical data. Interesting parallels exist between this hypothesis and the use of quiescent zones (gaps) in suggesting locations for large events at plate boundaries. For example, pre-event seismicity is lacking and the rate of occurrence of the largest events may be unrelated to the extension of the recursion relations for moderate and small earthquakes. For a physicalinterpretation, earthquakes too small to cause fracture through the crust may release stress at a rate different from the rate of stress release for major events. Other applications of statistics such as the probabilistic use of expert opinions offer a convenient way to dilute the implications of many hypotheses as well as anonymously eliminating the more incredible hypotheses.

RECOMMENDED RESEARCH

The explanation for the Charleston earthquake cannot be separated from an explanation for Eastern United States seismicity. Eventually the solution for both must incorporate a deterministic or predictive model consistent with the observed data and the applicable physical principles. It is difficult to assess at this time what new (or existing) geological or geophysical data will be most useful. Some real gaps do exist and not all data sets have been fully integrated into existing compilations. As a first step a computerized transportable data base needs to be developed for ease and uniformity in analysis of the Charleston area. Gaps in the data base could then be identified as likely targets for future data acquisition and research. New parameters could be added as sufficient data become available. Second, a need exists to emphasize basic research in two areas, numerical modeling of crustal deformations and mechanical properties of rocks as a function of pressure, temperature, composition, and stress.

Development of a transportable computer-based compilation of data for the Charleston area will allow identification of incomplete coverage, allow logical planning for future studies, and allow all investigators equal access to the same data set. Resolution of elements will have to vary. The smallest unit size would correspond to the 1/4-acre resolution of LANDSAT data and topography. The potential and geological data would be adapted best to an 0.5 to 1.0 km spacing. Regional data could be presented at a spacing of 4 to 8 km. The locations for all sets would be consistent, so that computations could easily include data sets at different resolutions. New data sets when made available could be incorporated into the total set. The total area of coverage should be at least 4 square degrees. The regional data should cover most of the Coastal Plain in South Carolina and southeastern Georgia.

The development of numerical modeling techniques will be necessary before the characteristics of crustal deformation and stress accumulation can be understood and predicted. Recent progress has been made in modeling rifting processes and rift propagation in two dimensions and in modeling homogeneous, viscous, or plastic crustal deformation. Although capable computers exist today, the three dimensional application of modeling to site specific intraplate problems is perhaps 2 to 4 years away because of the need to develop and implement techniques. The interpretation of material properties derived from geological and geophysical data may take even longer but will be a prerequisite to understanding why major events fail along multiple planes.

The second area of uncertainty is in the mechanical properties of rocks at the depths of major earthquakes. In particular, current hypotheses requiring different mechanical properties for mafic versus granitic crustal units are now highly speculative or circumstantial. Studies of granitic composition materials indicate transition to a ductile deformation mode at depths on the order of 10 km in contrast to deeper depths for mafic composition materials. Currently, these poorly constrained physical properties could predict a complex stress distribution with alternate crustal layering of elastic and ductile failure material with important consequences in crustal dynamics. The association of seismicity with mafic plutons or rifts of various ages must ultimately be related to a variation in mechanical properties and geometry. Before numerical models can be fully utilized, the combined effects of temperature, pressure, composition, and stress loading must be known. Finally new data will be needed to understand the influence of the free surface (or large contrasts in physical properties) on moderate and small earthquakes. While these small events may seldom be directly related to major earthquakes, they could provide a boundary condition for stress within the crustal plate. For these events, static friction, proportional to depth, is a controlling factor which could imply stress regimes very different from but related to those responsible for major events. Modification of free surface concepts may apply where low strength Coastal Plain sediments overlie crystalline basement rocks, as at Charleston, or where Paleozoic sediments overlie midcontinent crystalline rocks.

SEISMICITY IN THE EASTERN UNITED STATES AND THE ROLE OF CRUSTAL REFLECTIVITY

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THE PROBLEM

This short paper adresses the importance of crustal reflectivity as a requirement for the association of reflector geometry with hypocentral data. Locations of high crustal reflectivity that are coincident with current seismicity offer the best opportunity for associating hypocentral data with faults.

SUMMARY OF ACCOMPLISHMENTS

Fifty kilometers of multifold reflection seismic data were obtained during 1981 in the Charleston, South Carolina, area by the Virginia Tech VIGROSEIS crew in a cooperative program with the U. S. Geological Survey. The seismic data confirmed the absence of faults of large offset in the Cretaceous/-Teritary section. Two areas showed possible deformation of the sediments above the Jurassic basalt (J-reflector) that may be consistent with reverse faulting. See, for example, Line VT-1 (VP 50-110), Line VT-4 (VP 176-216) and Line VT-5 (VP 50-80), Figures 1, 2, and 3; however, curvature of reflections of Line VT-1 (Figure 1) might be caused by velocity pull-up associated with near-surface gravels of high velocity, and a minimum of faulting might be involved. Reflectors below the basalt on Lines VT-4 and VT-5 are deformed, suggesting either localized faulting of the basement, or primary depositional features. Excellent definition of a Mesozoic basin was obtained along Line VT-5 (Figure 3).

No strong reflections from within the crust are apparent on the VT lines. This is probably not a consequence of the high reflectivity at the top of the

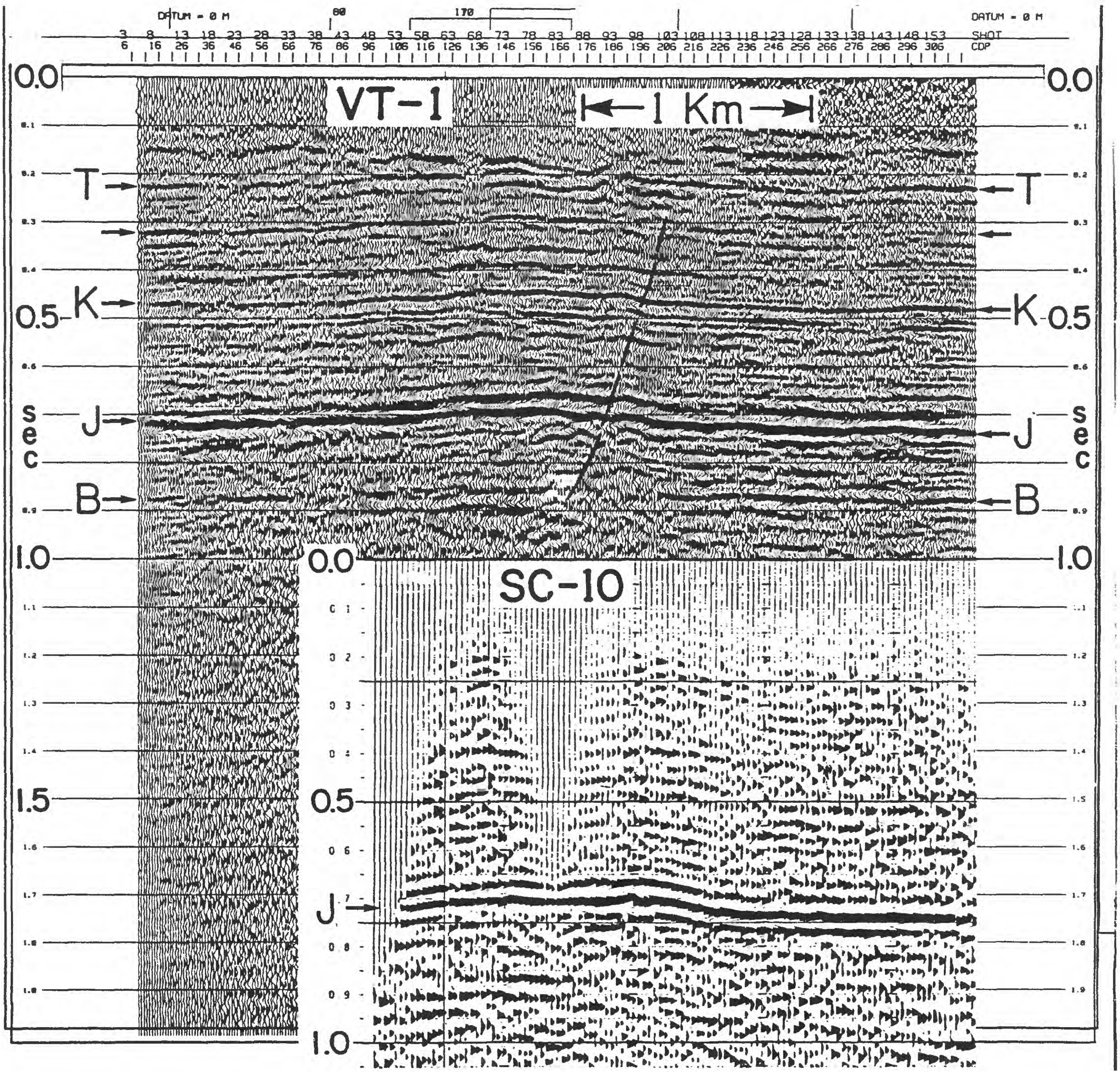

Figure 1.--Virginia Tech VIBROSEIS line VT-1 in Charleston area. B = Basement. J = Basalt. Single vibrator. Insert is line SC-10 by contractor over same portion of road. Three vibrators.

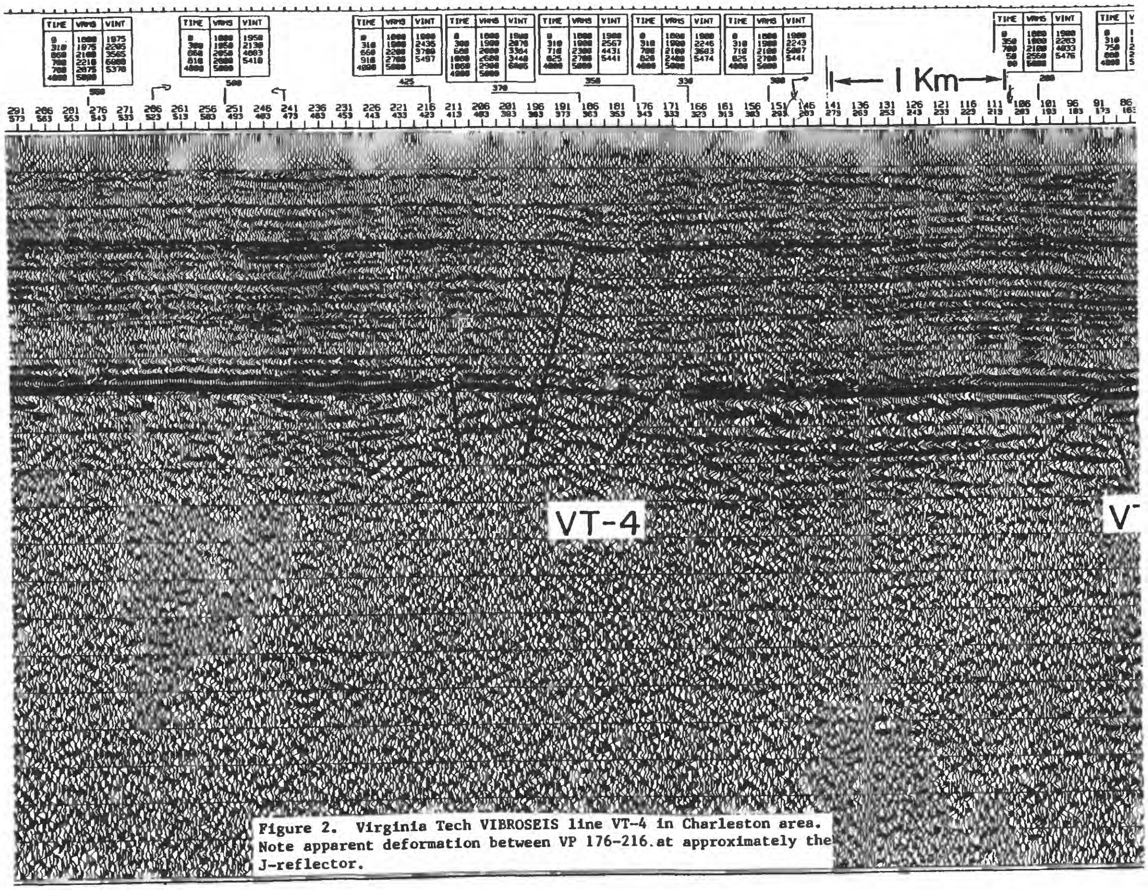

Figure 2. Virginia Tech VIBROSEIS line VT-4 in Charleston area. Note apparent deformation between VP 176-216 at approximately the J-reflector.

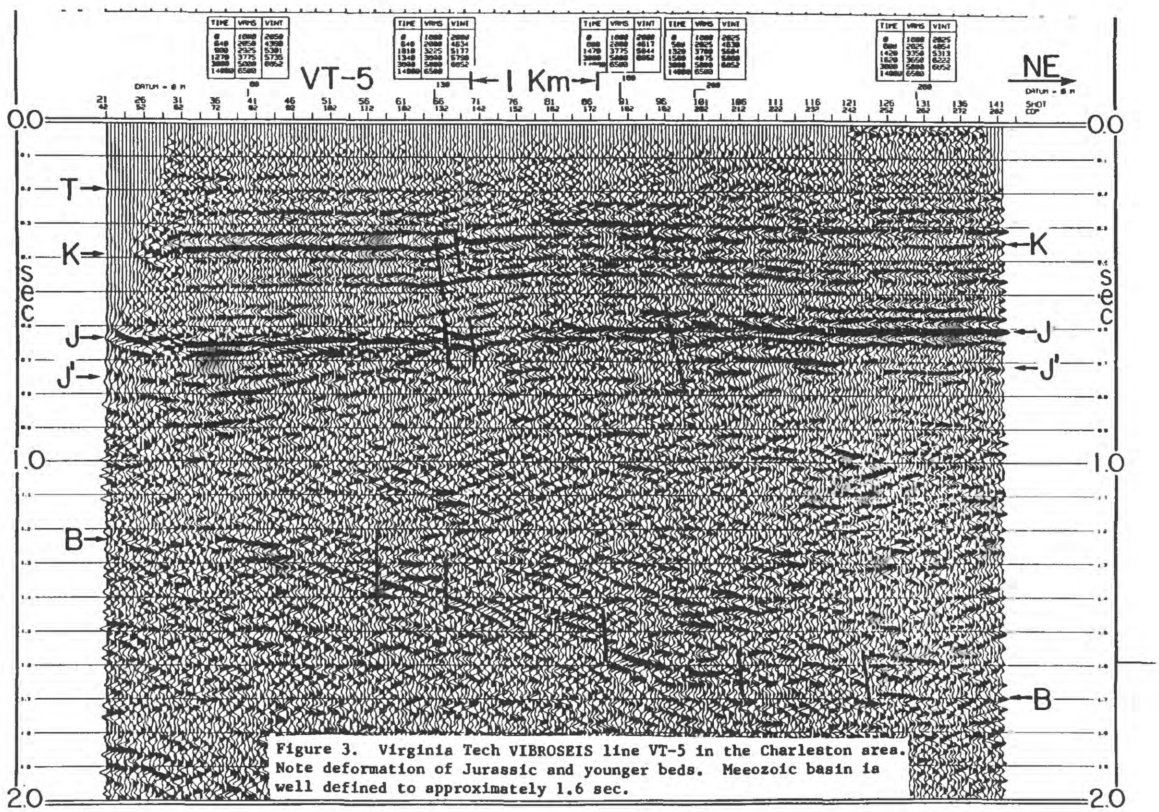

Figure 3. Virginia Tech VIBROSEIS line VT-5 in the Charleston area. Note deformation of Jurassic and younger beds. Mesozoic basin is well defined to approximately 1.6 sec.

basalt because it is the two-way transmission coefficient through the basalt that is important. For a reflection coefficient of 0.4 at the basalt/sediment interface, the two-way transmission coefficient is high, equal to 0.8. The amplitudes of seismic waves decrease on transmission from the Coastal Plain sediments into the basalt, but increase on the return path from the basalt into the sediments. In any event, excellent reflections from the top of basement (B) from below the basalt (J), and from the base of the Mesozoic basin are evident on VT Lines 1 and 5 (Figures 1 and 3, respectively). Other reasons for the low reflectivity of the crust at Charleston should therefore be sought.

Results to date of the Virginia Tech program in reflection seismology and regional tectonics indicate that, in general, the best crustal reflectivity is associated with either metamorphosed basalts and felsic volcanics, or with metamorphosed basalts and sandstones. The successful definition of the regional geologic framework of seismicity in the crystalline rocks of the Piedmont and beneath the Atlantic Coastal Plain depends, therefore, to a large extent on the placement of reflection seismology traverses where metamorphosed basalts/felsic volcanics, or metamorphosed basalts/sandstones are believed to occur in the subsurface. Both of these volcanic lithofacies are abundant in the Southeastern United States. For example, along the James River Traverse (JRT) in Central Virginia, Virginia Tech VIBROSEIS data confirm that Chopawamsic (continental margin) Slate Belt mafic and felsic volcanics are thrust over Precambrian Catoctin rift-related metamorphosed basalts and sandstones (Glover and others, 1982). The geometry defining this Taconic suture is clearly defined. In addition, the seismic signature of COCORP reflections from beneath the Elberton granite on Georgia Line 1 appears to us to be a volcanic signature. The signature is similar to one we obtained 360 km to the nothwest at Lumberton, N.C. (Pratt and others, 1982) where basement drill core obtained by Virginia Tech has tied excellent reflections to a thick (minimum 4.5 km) sequence of metavolcanics similar to those exposed in the Slate Belt to the northwest. A portion of our Lumberton data is shown in Figure 4. If the Charleston area is underlain locally by non-volcanic crystalline basement, then the basement may be acoustically transparent, and unable to reflect energy that could define internal geometry. Definition of the geologic framework of Charleston seismicity, and the probability of

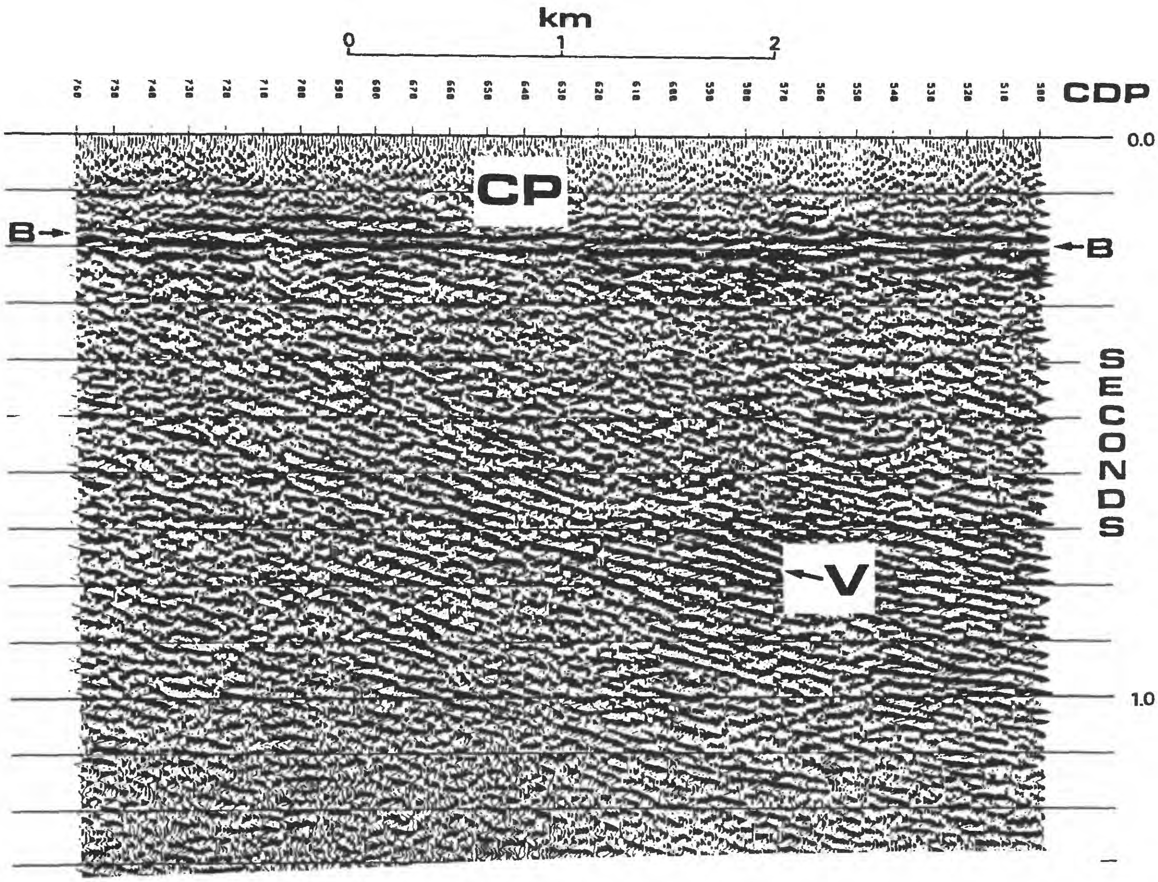

Figure 4.--Detail of upper portion of the seismic line showing the dipping volcanic layers (V) truncated against the Coastal Plain sediments (CP) at the basement reflector (B).

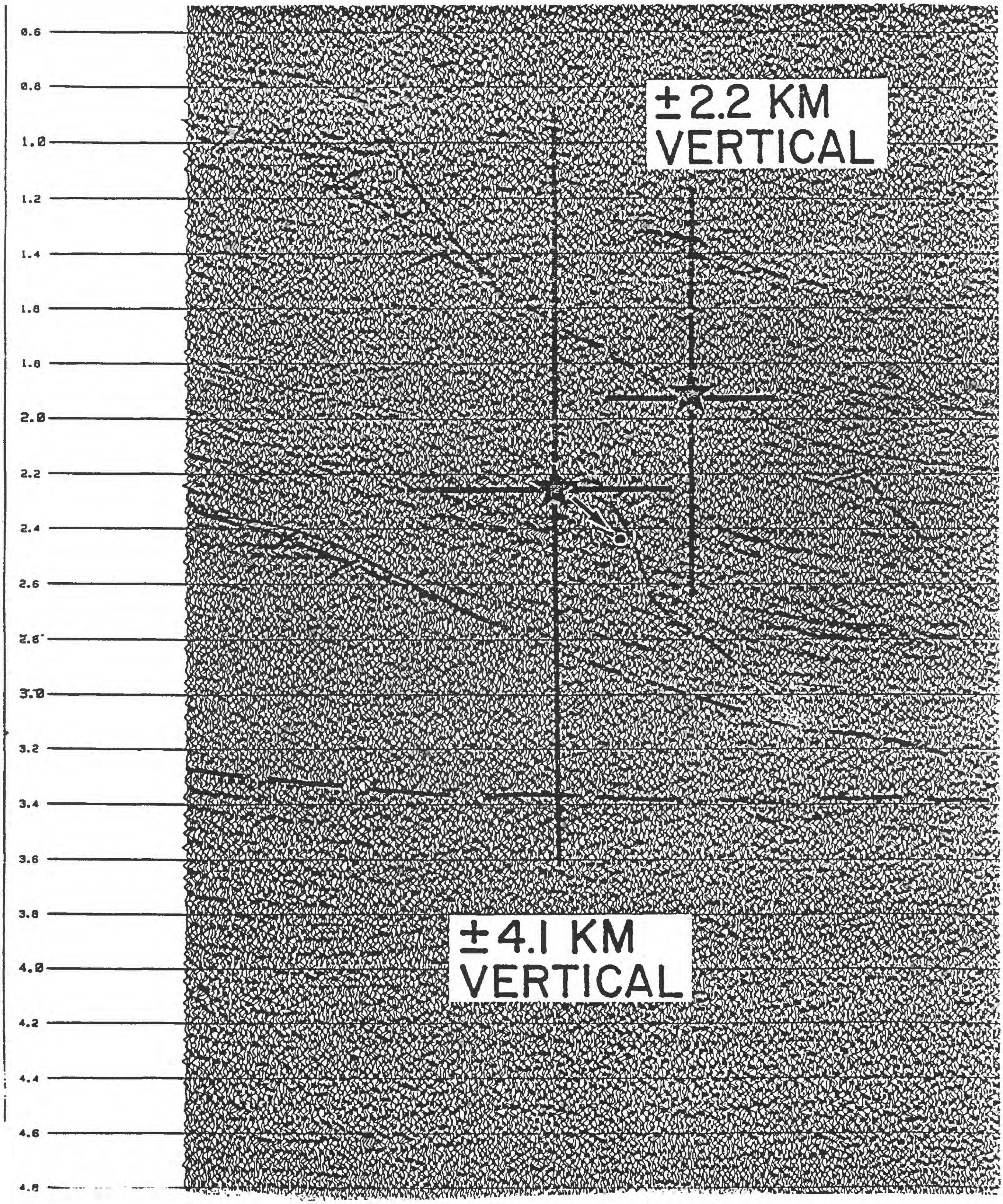

Figure 5.--Virginia Tech VIBROSEIS line NRC-4 along James River Traverse (JRT) in Central Virginia. Hypocentral data plotted from Bollinger (personal communication, 1982) Reflection seismic data are migrated.

Charleston-type earthquakes occuring elsewhere in the Eastern United States may therefore require additional regional as well as local reflection seismic data. We suggest that the steep part of the Appalachian gravity gradient is an important guide to selecting locations for additional regional data as well as identifying locations of potential seismogenic structures in the Eastern United States.

There is general agreement that the Appalachian gravity gradient from Alabama to Vermont marks a fundamental change in the continental crust for the entire length of the Appalachians (Gravity Anomaly Map of the United States, 1982; Cook and Oliver, 1981). We designate here the regional Appalachian gravity gradient (±100 km in width) as the gravity gradient, GG, and the steepest parts of the gradient (±10 km in width) as SPGG, or SPGG', depending on whether the source of the steep part of the gradient is, respectively, exposed or believed to be buried in the upper crust. We designate the source of the steep part of the gravity gradient with primed quantities where we believe it to be mostly autochthonous. We thus divide the Appalachian gravity gradient, GG, into three parts: GG, SPGG, and SPGG'. The regional(+100 km) slope of the gravity gradient, GG, is believed to be caused by crustal thinning at the M-discontinuity (James and others, 1968). The source of SPGG or SPGG' is not well understood; a correct identification of the source could be a major factor in understanding the geologic framework of eastern seismicity.

The JRT has contributed much to our understanding of the source of the steep part of the gravity gradient. In central Virginia, along the James River Traverse, the steep part of the gravity gradient (SPGG) occurs on the flank of the Blue Ringe directly over the allochthonous rift facies Catoctin and Lynchburg Formations. The seismic data clearly indicate that the Catoctin and Lynchburg are allochthonous here, and suggest that the source of SPGG is the thick edge of the sequence of exposed allochthonous rift-related Catoctin metabasalts and metasandstones. Along the JRT, excellent events from below Catoctin reflections could originate from a duplicated thickness of Catoctin, or from unmetamorphosed lower Paleozoic carbonates and Rome Fm. Additional 24-fold data may be required to differentiate between these two models along the JRT and to reconcile the interpretation of the seismic data with geologic models developed elsewhere on the Blue Ridge.

An important conclusion is the interpretation of the source of the steep part of the gravity gradient as everywhere a structural edge , but not necessarily attributable everywhere just to the Catocin. If this model is correct, The JRT is a significant tie point for the interpretation of geophysical data to the north and south. Finally, along the JRT southeast of SPGG, we believe we have correlated hypocentral data with faults interpreted from seismic data at hypocentral depths (Figure 5; Bollinger and others, 1983), and that SPGG might serve as a guide to other such correlations in the East.

In Georgia, the steep part of the gravity gradient is approximately coincident with eastward-dipping reflections from beneath the Elberton granite in Georgia from 2.5 sec (8 km) to 5.5 sec (18 km) (and same data reprocessed by Iverson and Smithson, 1982) from the Georgia COCORP line (Cook and others, 1981, their Fig. 7). We believe that these reflections originate from a thick sequence of thrust-duplicated rift-related metamorphosed volcanics and standstones, but that here the rift volcanics are partly in place against the margin of the Proterozoic continent.

In summary, we suggest that the source of the steep part of the Appalachian gravity gradient is a tectonically thickened edge of rift-related metamorphosed basalts and sandstones, in a geologic setting either similar to SPGG along the James River traverse in Virginia where the rift sequence is allochthonous facies concealed beneath the Carolina Slate Belt and Charlotte Belt in Georgia and North Carolina (SPGG').

Figures 6-8 show the relationship of the steep part of the gravity gradient to instrumentally determined epicenters in New Jersey, central Virginia, and South Carolina and Georgia, respectively. Hypocenters appear to be coincident with, or are located within 100 km to the southeast, of SPGG (or SPGG'). Although any genetic relationship between SPGG, SPGG', an edge of rift volcanics, and earthquake hypocenters has yet to be established, there appears to be a spatial correlation in central Virginia along the JRT where most of the hypocenters are southeast of, but within about 100 km of, SPGG. This area corresponds with tectonically thickened volcanic (sedimentary) lithofacies along the eastern edge of the Late Precambrian-Early Paleozoic continental margin. The association of SPGG with an edge of rift-related volcanics

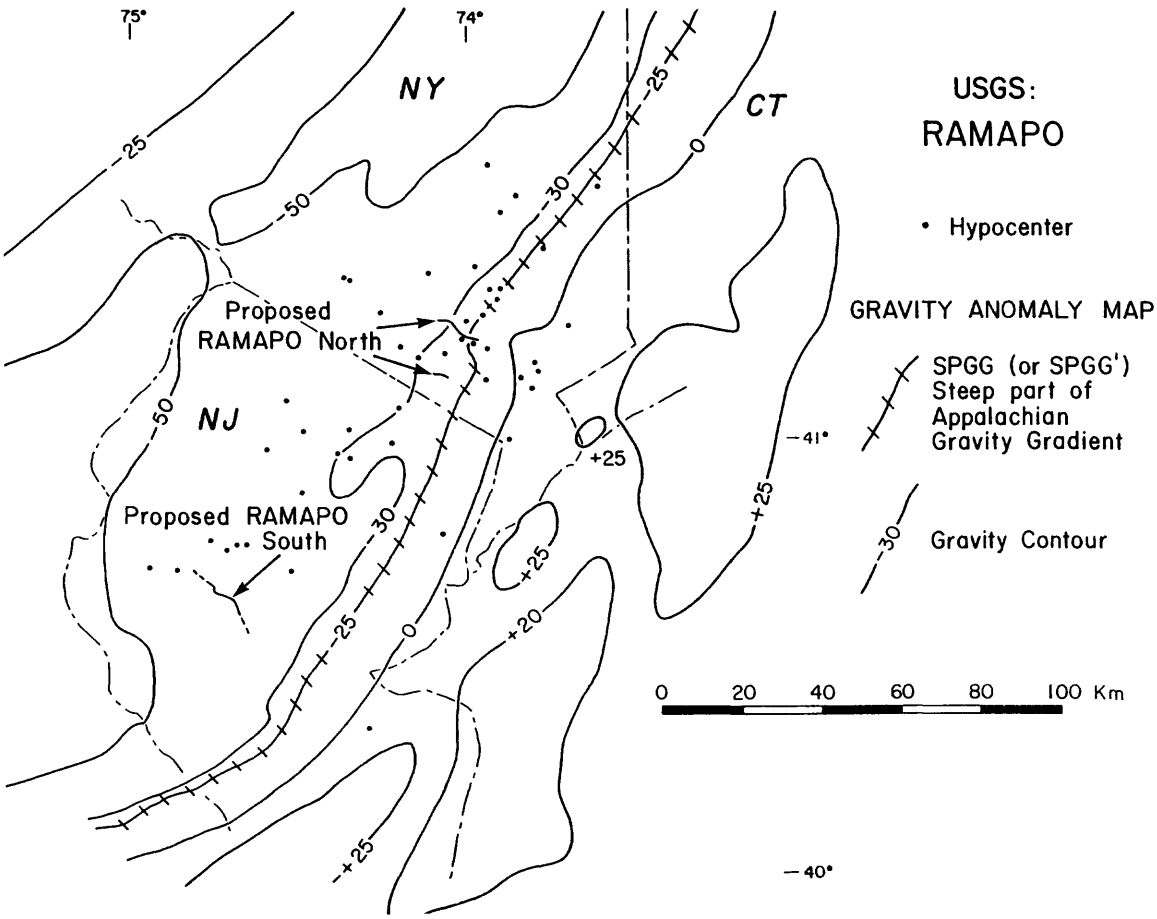

Figure 6.--Steep part of Appalachain gravity gradient at ramapo fault zone in New Jersey (SPGG'?). Also shown are hypocentes greater than 5 km in depth.

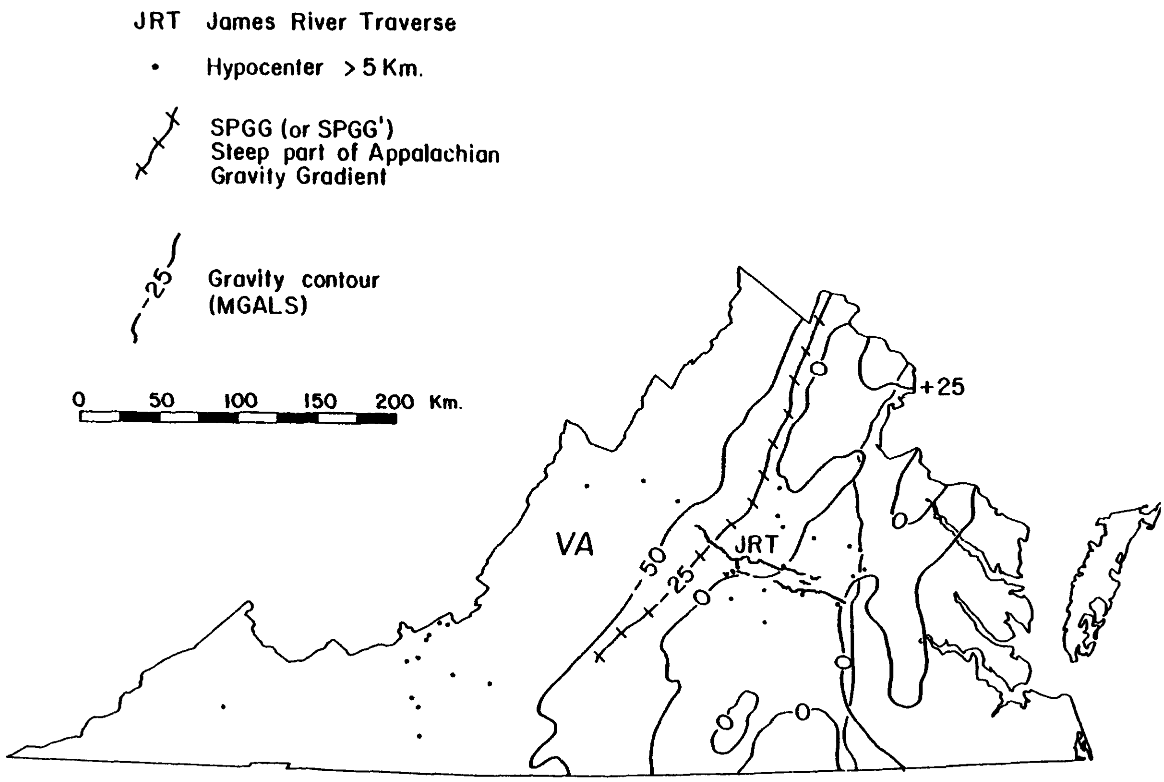

Figure 7.--Steep part of Appalachian gravity gradient in Virginia (SPGG). Also shown are hypocenters greater than 5 km in depth. Also shown is the James River VIBROSEIS Traverse.

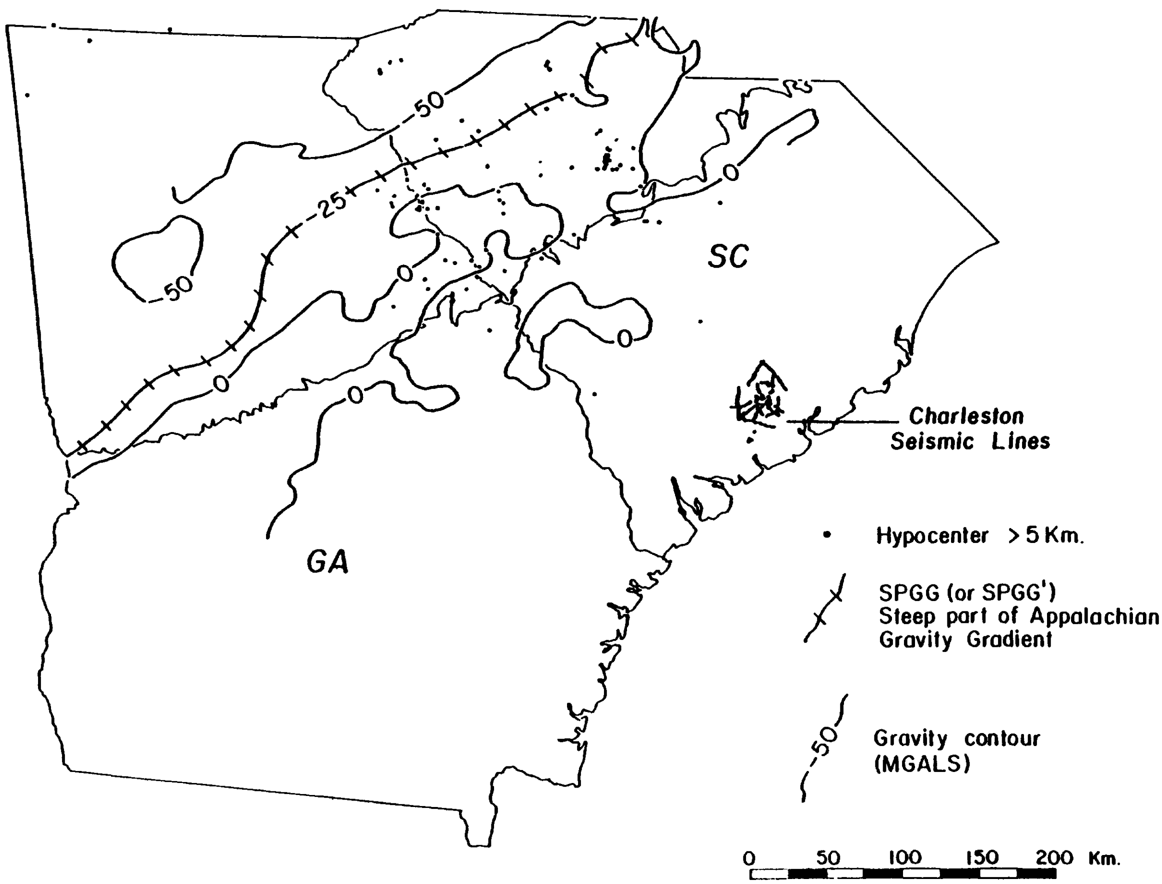

Figure 8.--Steep part of Appalachian gravity gradient in South Carolina and Georgia (SPGG'). Also shown are hypocenters greater than 5 km in depth.

appears to be unambiguous in central Virginia. Whether SPGG is similarly related to tectonically thickened rift volcanics in South Carolina and New Jersey has not been established; if the correlation is generally correct, then crustal reflectivity and the opportunity for correlation of hypocentral data with faults should be excellent beneath SPGG or SPGG'. We propose that the source of SPGG (SPGG') represents an important structural edge and that further confirmation of the lithology of the source is important. Because of the proximity of SPGG to earthquake hypocenters, reflection seismology traverses over SPGG both in areas where seismicity is known to occur and where it is not, offer the best opportunity for correlation of reflector geometry with hypocenters, and attempting to understand the differences between seismic and aseismic regions.

The distribution of eastern seismicity in currently active clusters and active linear and diffuse zones (e.g., Bowman, Charleston, Giles County, Central Virginia, Rampo, etc.) suggests that the interative use of active and passive seismic methods can successfully define the correlation between hypocenters and tectonic structures, if the structures are reflective. After an association of hypocentral data with faults has been established, the causative mechanism for seismicity (backsliding, reactivation by compression, or other mechanisms) may become clear.

RECOMMENDED RESEARCH

We suggest that the apparent correlation between eastern seismicity and SPGG (SPGG') be examined in detail by multifold reflection seismology profiles along traverses that begin just northwest of SPGG in South Carolina and North Carolina, and extend to the southeast. In South Carolina, the above-mentioned regional reflection traverses should be extended into Charleston to complement the Georgia COCORP line and provide the data necessary to place the Charleston area in a more understandable regional geoligic framework.

We propose to purchase and reprocess available seismic data (SEISDATA and PETTY-RAY) that cross SPGG and/or SPGG' in the Eastern United States, in order to examine crustal reflectivity and the source of SPGG (SPGG') in these areas. Several line segments will be coincident with seismically active areas.

The results thus far from local network monitoring of seismicity in the Charleston locale dictate a need for additional reflection data locally, with higher fold and with shear vibrator sources. Shear vibrators are superior to P sources on hard (carbonate) surfaces (personal communication, Ken Waters, Conoco, Inc.), although they have not yet been tested on crystalline terrain. In addition, non-standard acquisition and processing steps such as recording single sweeps from a single vibrator for the purpose of beam-forming should increase the resolving power of reflection data.

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SCIENTIFIC CONTRIBUTIONS AND FUTURE USES OF SEISMIC NETWORKS IN THE CHARLESTON, SOUTH CAROLINA, AREA

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The purpose of this paper is to discuss the role of the South Carolina Seismic Network in investigations of Charleston-area earthquakes. Details of the history and operation of the network will not be addressed here nor will be areas away from Charleston (for such information refer to Tarr et al (1981), Tarr and Rhea (1983), and Tarr (1977)). We will instead state some principal conclusions that have been reached through consideration of network data, mention some unsettled issues, and suggest some approaches for using network data to resolve these issues.

The most fundamental conclusion that has been made possible by network data is that earthquakes in the Coastal Plain of South Carolina are clustered within source zones whose lateral extent is a few tens of kilometers and which lie at depths between some 5 to 13 km (Tarr and Rhea, 1983). This result has been directly demonstrated for the events recorded by the network. Furthermore, events recorded at regional and teleseismic distances before network installation have been relocated using network data for calibration (Dewey, 1983), and these older events appear to fall in the same source zones as the local events. This concentration of earthquakes in relatively small regions is not something that would have been anticipated on the basis of pre-network locations alone. Indeed, the older locations were scattered widely in the coastal plain, giving an appearance of more diffuse seismicity throughout South Carolina than actually existed.

The localization of most coastal plain seismicity in small regions is a fundamental result that has had important effects on seismotectonic theories of the Charleston area. In particular, the localization of earthquake sources suggests there exist localized seismogenic structures with which past and future earthquakes can be associated, and, in fact, geophysical data confirm the presence of various basement structures in close association with earthquake focii (Tarr et al, 1981; Tarr and Rhea, 1983; Phillips, 1977; Long and Champion, 1977). It is evident that if seismogenic structures and the cause of earthquakes upon them could be identified, one would have in hand an important tool for estimating the likelihood and size of earthquakes near Charleston or in other tectonically similar regions. The earthquake location results have, therefore, had the effect of stimulating the search for specific structural features near Charleston (Hamilton et al, 1983; Behrendt et al, 1983; Ackerman, 1983).

First motions form another fundamental data set from the seismic network. These have had more equivocal tectonic interpretation than the earthquake location data. Composite fault plane solutions based on first motions show nearly vertical planes whose strikes range from northeast to northwest, with reverse or strikeslip movement (Tarr and Rhea, 1983; Talwani, 1982; Tarr et al, 1981; Amick, 1977). A horizontal fault plane, conjugate to the reverse faults, has also been proposed (Seeber and Armbruster, 1981) as the source of the 1886 earthquake. The most common and perhaps best-established result of the fault-plane solutions is the determination of a nearly horizontal P-axis trending southwest.

At present, uncertainties in location and first-motion data are the limiting factors in improving the resolution of seismogenic structures and earthquake mechanisms at Charleston. The better-determined hypocenters calculated from network data, using the model of Tarr et al (1981), have average uncertainties (68 percent confidence level) of about 1.0 km horizontally and 2.4 km vertically (Table 1). Comparisons of hypocentral solutions for various laterally-homogeneous crustal models of the area (Tarr et al, 1981; Talwani, 1982; Amick, 1977) show that changes in locations between models are typically less than uncertainties in location (Table 2). Location uncertainties, combined with any biasing or scatter of hypocenters due to inadequate

DATE	H M	SEC	LAT(N)	LON(W)	Z	DZ	M	N	A	AZ	B	AZ	Q
741122	525	56.24	32.921	80.144	7.6	2.9	3.8	10	2.0	-12.3	1.0	-102.3	C
750428	546	52.61	33.000	80.216	10.5	2.1	3.1	9	1.2	-15.2	0.8	-105.2	C
761114	2112	11.94	32.955	80.184	6.0	4.2	1.3	8	1.8	-14.3	1.0	-104.3	B
770118	1829	14.23	33.041	80.214	7.1	1.4	2.7	15	1.5	2.2	0.7	-87.8	B
770120	4 5	45.69	32.929	80.159	7.9	2.1	1.9	12	1.3	-59.1	0.9	30.9	B
770226	10 9	56.12	32.922	80.178	5.4	1.2	1.6	8	0.6	-12.4	0.4	-102.4	B
770318	736	8.56	32.936	80.176	5.4	2.8	1.2	6	1.2	-13.1	0.7	-103.1	B
770330	827	47.77	32.955	80.184	8.4	1.0	2.9	15	0.7	8.2	0.5	-81.8	B
770531	2350	13.34	32.940	80.227	13.1	4.3	2.6	9	2.6	11.7	1.4	-78.3	B
770823	1344	59.98	32.937	80.161	8.2	2.2	2.3	8	1.2	-50.0	0.9	40.0	B
771215	715	55.09	32.983	80.267	14.6	2.2	2.1	16	1.1	22.1	0.8	-67.9	B
771215	1916	43.58	32.943	80.165	8.7	1.5	2.6	17	1.0	-15.8	0.7	-105.8	A
771220	2341	23.13	33.067	80.231	13.5	9.0	1.8	7	3.6	-12.0	2.3	-102.0	C
780907	2253	22.97	33.061	80.213	9.9	1.0	2.6	19	0.7	-123.5	0.5	-33.5	A
781030	915	6.50	33.043	80.153	5.9	1.5	---	8	0.5	29.9	0.5	-60.1	B
781030	915	13.08	33.043	80.154	5.5	1.6	1.8	7	0.5	-74.1	0.4	15.9	B
781030	916	2.76	33.042	80.162	6.4	4.8	---	7	1.5	-24.0	1.3	-114.0	B
781030	916	14.70	33.033	80.153	7.0	3.6	2.5	10	1.5	-89.3	1.4	0.7	B
790127	2355	15.66	33.056	80.182	6.6	3.3	2.8	14	1.4	-123.2	1.1	-33.2	B
790811	211	56.46	32.987	80.228	12.6	3.1	2.5	13	1.9	36.9	1.2	-53.1	B
791021	710	28.87	32.928	80.193	8.7	6.1	1.6	6	3.0	-34.5	1.1	-124.5	C
791207	543	34.95	33.006	80.169	4.0	1.8	2.8	15	0.7	-108.3	0.6	-18.3	B
810319	433	55.37	32.960	80.188	5.9	2.4	2.3	16	1.2	43.4	0.8	-46.6	B
810326	912	50.89	32.977	80.216	9.5	7.5	1.4	6	4.0	-59.5	2.9	30.5	C

TABLE 1. CATALOG OF SELECTED EARTHQUAKES IN MIDDLETON PLACE-SUMMERVILLE AREA. LOCATIONS CALCULATED USING HYPOELLIPSE PROGRAM (LAHR,1979). SYMBOLS: Z, DEPTH; DZ, DEPTH UNCERTAINTY; M, CODA MAGNITUDE; N, NUMBER OF READINGS; A AZ, B AZ, HORIZONTAL ERROR ELLIPSE AXES AND AZIMUTHS; Q, QUALITY. THESE LOCATIONS ARE CALCULATED USING THE RHEA MODEL (TARR ET AL, 1981). S-WAVE TIMES FROM A SINGLE THREE-COMPONENT STATION WERE USED, WHEN AVAILABLE; OTHERWISE, P-WAVE TIMES ONLY WERE USED.

TABLE 2. DIFFERENCES BETWEEN LOCATIONS AND ERROR ELLIPSES FOR VARIOUS CRUSTAL MODELS OF THE CHARLESTON AREA. DIFFERENCES ARE FORMED BY SUBTRACTING PARAMETER VALUES FOR THE STANDARD MODEL FROM CORRESPONDING VALUES FOR THE NEW MODEL. ALL DIFFERENCES ARE IN KILOMETERS. SYMBOLS: DLAT, DLON, DZ ARE DIFFERENCES IN LATITUDE, LONGITUDE, AND DEPTH, RESPECTIVELY; NEL IS MEAN HORIZONTAL ERROR ELLIPSE AXIS FOR THE NEW MODEL, NZEL IS VERTICAL ERROR ELLIPSE AXIS FOR THE NEW MODEL; DEL, DZEL ARE DIFFERENCES IN MEAN HORIZONTAL AND VERTICAL ERROR ELLIPSE AXES. (FOR MODELS SEE TARR ET AL, 1981; TALWANI, 1982; AMICK, 1977.) NOTE THAT POSITIVE VALUES OF DLAT, DLON, DZ IMPLY NORTHWARD, EASTWARD, AND DOWNWARD CHANGES IN LOCATION FOR THE NEW MODEL WITH RESPECT TO THE STANDARD.

A) STANDARD MODEL = RHEA; NEW MODEL = TALWANI

DATE	TIME	DLAT	DLON	NEL	DEL	DZ	NZEL	DZEL
741122	525	1.7	0.2	0.6	-0.9	-1.4	1.0	-1.9
750428	546	1.1	0.4	0.3	-0.8	-1.8	0.5	-1.6
761114	2112	0.4	0.4	1.6	0.2	-2.9	14.2	10.0
770118	1829	0.0	1.2	1.5	0.4	0.7	2.4	1.0
770120	4 5	-0.1	0.8	1.0	-0.1	0.0	1.4	-0.7
770226	10 9	0.6	0.6	0.3	-0.2	0.2	0.6	-0.6
770318	736	0.1	0.7	0.5	-0.5	-0.1	1.4	-1.4
770330	827	0.1	0.8	0.4	-0.2	-1.8	0.7	-0.3
770531	2350	0.2	0.7	1.1	-0.9	-1.6	3.2	-1.1
770823	1344	0.0	0.7	1.0	-0.1	-0.6	1.5	-0.7
771215	715	0.3	1.1	0.7	-0.3	-1.9	1.5	-0.7
771215	1916	0.4	0.4	0.6	-0.3	-1.4	0.8	-0.7
771220	2341	-0.8	1.8	2.8	-0.2	-0.7	7.5	-1.5
780907	2253	-0.2	0.4	0.4	-0.3	-0.6	0.5	-0.5
781030	915	-0.6	0.1	0.5	0.0	-1.0	1.2	-0.3
781030	915	-0.6	0.1	0.4	-0.1	0.0	1.5	-0.1
781030	916	-0.4	0.4	0.8	-0.6	-0.3	2.9	-1.9
781030	916	0.2	0.1	0.7	-0.8	0.0	1.3	-2.3
790127	2355	-0.8	0.8	0.4	-0.9	1.7	0.7	-2.6
790811	211	0.3	1.4	1.0	-0.6	-1.7	1.9	-1.2
791021	710	0.4	1.3	1.8	-0.2	0.2	2.4	-3.7
791207	543	0.2	0.3	0.6	-0.1	1.2	0.9	-0.9
810319	433	-0.4	1.4	1.4	0.4	1.2	2.5	0.1
810326	912	-0.1	0.3	4.0	0.5	0.4	5.1	-2.4

B) STANDARD MODEL = RHEA; NEW MODEL = AMICK

DATE	TIME	DLAT	DLON	NEL	DEL	DZ	NZEL	DZEL
741122	525	-2.0	0.3	1.7	0.2	2.3	2.9	0.0
750428	546	-1.4	0.2	1.5	0.5	3.1	2.7	0.6
761114	2112	-0.2	0.4	2.0	0.6	-0.8	7.7	3.5
770118	1829	-0.7	0.7	1.7	0.6	4.0	1.7	0.3
770120	4 5	-0.2	0.0	1.4	0.3	0.7	2.8	0.7
770226	10 9	-0.6	0.4	1.3	0.8	2.0	3.0	1.8
770318	736	-0.6	0.7	1.4	0.4	0.6	4.0	1.2
770330	827	-0.8	0.3	1.0	0.4	1.3	1.6	0.6
770531	2350	-0.2	0.8	2.2	0.2	0.8	4.8	0.5
770823	1344	-0.9	0.3	2.3	1.2	1.6	4.9	2.7
771215	715	-1.0	0.2	1.4	0.5	2.3	3.1	0.9
771215	1916	-0.2	0.0	0.9	0.1	0.6	1.6	0.1
771220	2341	-0.2	0.9	2.4	-0.5	1.9	7.8	-1.2
780907	2253	-0.3	-0.6	1.0	0.4	2.7	1.5	0.5
781030	915	0.0	-0.2	0.8	0.3	2.6	2.2	0.7
781030	915	-0.1	0.2	0.9	0.4	1.8	2.8	1.2
781030	916	-0.1	0.6	1.1	-0.3	1.6	3.8	-1.0
781030	916	-0.4	0.0	1.8	0.4	0.0	5.1	1.5
790127	2355	0.0	0.0	1.3	0.0	1.1	3.5	0.2
790811	211	-0.1	0.6	1.7	0.1	2.1	3.4	0.3
791021	710	-1.2	1.9	3.3	1.3	4.7	8.5	2.4
791207	543	-0.1	-0.3	1.1	0.4	0.5	3.2	1.4
810319	433	-0.3	0.6	1.4	0.4	0.6	3.6	1.2
810326	912	-0.1	0.0	3.9	0.4	0.8	8.7	1.2

modeling, are sufficient to obscure linear patterns or surfaces formed by hypocenters, and make it difficult to say whether or not particular groups of focii are coincident with particular structures inferred from various geophysical data. The uncertainties in location are also sufficient to make it difficult to separate earthquakes strictly on the basis of location into tectonically related groups for composite fault plane solutions. The fault plane solutions are also affected by uncertainties in instrument polarity, by emergent arrivals for smaller earthquakes, and by assumption of laterally homogeneous crustal models in a demonstrably heterogeneous area. These factors combine to admit the conflicting fault plane solutions, as noted above, any one of which may have 10 to 20 percent inconsistent first motions.

The weak trends in epicenters that have been postulated near Charleston, as well as the proposed high-angle fault plane solutions, suggest seismogenic structures aligned at 25 to 90 degrees to the large-scale northeast-trending structural grain that is exposed in the Piedmont and Appalachians and might also be expected in Coastal Plain basement rocks at Charleston. Thus, while the network data clearly show localization of source zones and strongly suggest local structural control of earthquake locations, the same data do not demonstrate any unequivocal alignment between expected major structural trends and present earthquake hypocenters or fault planes. In particular, no strong support may be drawn from network data for reactiviation of preexisting northeast-striking vertical structures, for the existence of reverse motion on northeast-striking listric faults, or for involvement of a horizontal fault plane in current seismicity (Behrendt et al, 1981; Seeber and Armbruster, 1981).

Major unresolved issues are, whether or not northeast-striking structures are currently active in the Charleston area, whether or not there are active northwest-striking structures of sufficient size to produce the 1886 earthquake, or whether some other mechanism, such as a horizontal detachment or north-northeast-trending strike-slip fault may be possible.
In terms of understanding the 1886 earthquake itself, and in terms of extrapolating from Charleston to other areas of the Eastern United States, these questions are paramount.

The current limits of resolution of source structures and source mechanisms in the Charleston area has its origin at least in part in the nature of the current seismic network and the environment in which it operates. The network is composed of vertical-component, short period, high-gain instruments, with limited dynamic range. It is designed and operated to record the arrival of P-waves, and therefore produces P-wave times and first motions; any other capability, such as on-scale recording of entire P-waveforms of larger events, is incidental. Such a design is most appropriate to an initial stage of investigation where little is known about locations of earthquakes and some broad location capability is desired for an area, or for an ongoing seismicity-monitoring effort. It is not well-suited for more extensive or sophisticated data analysis. Locations of earthquakes and crustal modeling efforts will necessarily be limited to those based on P-wave arrival times and waveform modeling will be limited to the vertical component of those events that are on scale.

In any network, the number of events recorded will be limited at low magnitude by signal-to-noise ratios and at high magnitude by recurrence rates. At Charleston, in particular, signal-to-noise is relatively low for the present network, and recurrence rates are low, resulting in a narrow magnitude window for recorded events. A frequency-magnitude plot for 1973-1981 is shown in Figure 1. It is apparent that earthquakes with magnitudes below 2 are underrepresented and events with magnitudes above 3 rather infrequent.

We suggest that there are several steps that should be taken with respect to the network to improve its potential for resolving some of the seismotectonic issues mentioned above. First, methods of increasing the signal-to-noise ratio of the seismic network should be found. These might involve systematic searches for less noisy surface sites, installation of downhole instruments, or signal processing techniques such as array summing or filtering. The effect of signal-to-noise improvement would be to make a larger number of small-magnitude events available for recording and would provide both location and mechanism information at a higher rate than is presently possible. For example, Figure 1 suggests 100 events or more with magnitude between 1.0 and 2.0 have not been adequately recorded during the life of the network. Second, to take full advantage of increased network sensitivity and to permit full waveform recording for larger events, the dynamic range of the network should be increased through use of multiple gains, gain ranging, digital recording or some combination thereof. Third, in order to record complete waveform data, and better define locations, source mechanisms, crustal structure and physical properties, stations should record both vertical and horizontal components of motion. Steps have recently been taken in the Charleston area to implement these suggestions with the installation of some downhole instruments and 4 dual-gain three-component stations. Nevertheless, more improvements are required.

All of the above amounts to a prescription for the ideal network, with maximum sensitivity, dynamic range, and bandwidth. Unfortunately, in the Charleston area it appears that something closer to this ideal is going to be necessary before a significant advance can be made in addressing the important seismotectonic questions that remain. This is not likely to be cheaply done. However, we suggest that the present network is ill-suited to provide the kind of data needed to further investigate or test the tectonic hypotheses that have been advanced for the Charleston area, regardless of the fact that these hypotheses may have been suggested by network data originally. Therefore, it may be necessary to redistribute available funds to test the more important hypotheses concerning the Charleston seismic source zones. It may be necessary to reorder or curtail activities of the present State-wide network, admitting that it has done valuable service but recognizing it serves a limited purpose. In this way, sufficient funds may be made available to study more particular problems in a timely way.

Assuming for the moment that such action were taken, the data resulting from a new, concentrated network should be used to model, in as much detail as possible, crustal structure, crustal properties, and seismic sources. Full advantage should be taken of the various sorts of geophysical data (gravity, aeromagnetic, reflection, refraction) that have been gathered to date, in order to define crustal models, and full-waveform modeling should be done to define source mechanisms. Relative location schemes should be employed to test for alignments or systematic trends in locations. Again, several of these approaches are currently being taken, using existing data, but as we have pointed out, these data are limited in quality and quantity. It is hoped that combination of improved data and more complete modeling and analysis techniques will allow significant progress to be made in addressing the Charleston problem.

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THE ROLE OF VERTICAL CRUSTAL MOVEMENTS AND REGIONAL GEOLOGIC ANALYSIS IN EVALUATION OF THE 1886 CHARLESTON, SOUTH CAROLINA EARTHQUAKE

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INTRODUCTION

The previous discussions in this session regarding the various hypotheses surrounding the occurrence of the 1886 Charleston, South Carolina, Earthquake bring to mind several generic questions. These questions will need to be resolved so that our current state of knowledge of the Charleston region can be refined and advanced to the point of being able to realistically assess the probability of a large earthquake occurring elsewhere in the eastern seaboard.

WHAT IS THE RELATIONSHIP OF CRUSTAL STRAINING DURING THE CENOZOIC TO HOLOCENE CRUSTAL STRAINING IN THE COASTAL PLAIN OF SOUTH CAROLINA?

The resolution of this question will require an understanding of the continuum of development of the continental margin in southeastern North America since the Cenozoic, whether it is temporally constant or evolving in discreet, but random, periodic "bursts". The temporal and spatial characteristics of deformation in the continental margin need to be assessed as to the recurrence rates of earthquakes large enought to leave their "record" in the geologic column in the coastal plain. Factors that will be important are:

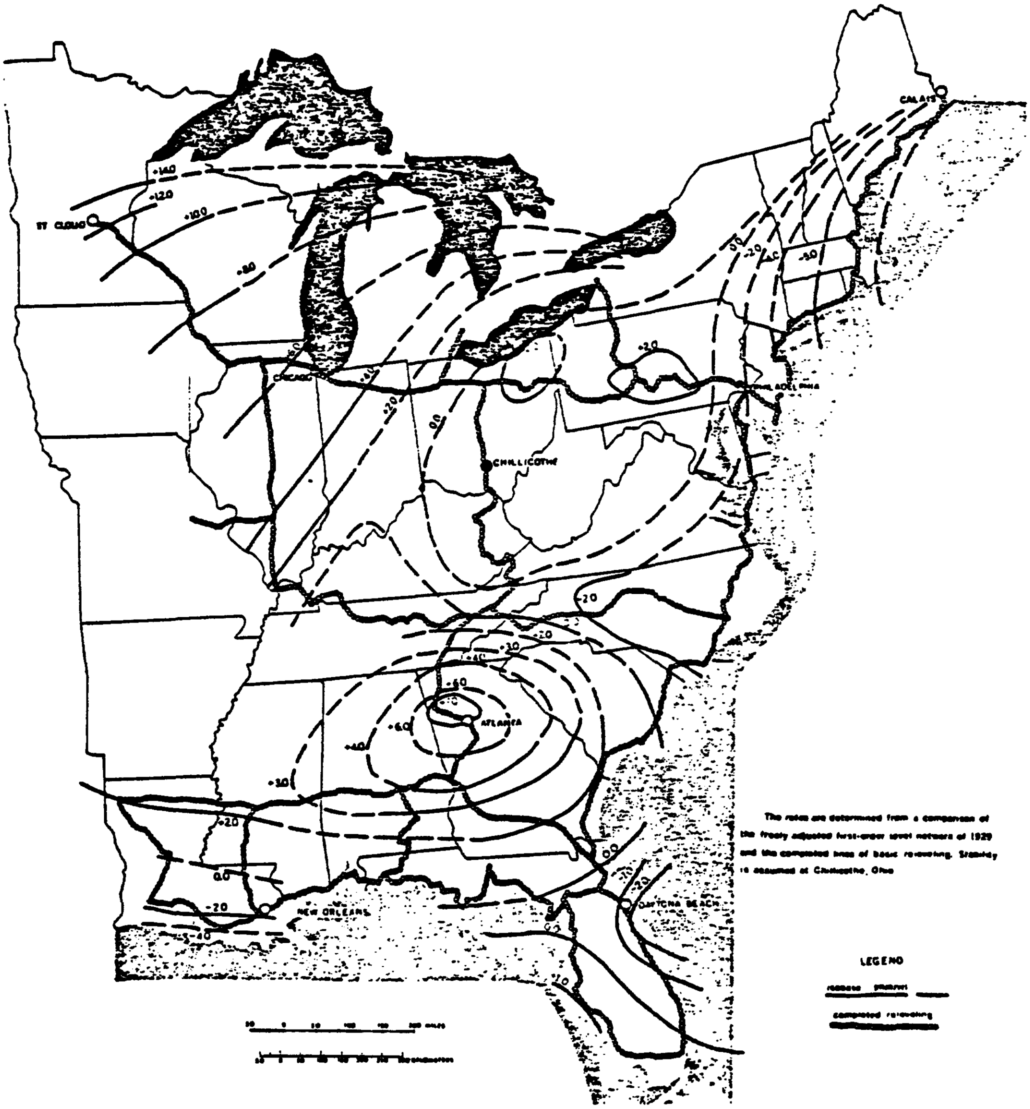
1) Comparison of deformation structures in the Cenozoic sediments to those in Holocene sediments:

   Many investigators have reported various types of deformation structures in the Coastal Plain sediments of eastern North America. These structures vary from high angle reverse faults to clastic dikes and liquefaction type structures throughout late Cretaceous to mid Tertiary sediments. Some have disturbed younger sediments as well. In order to better understand their genesis, and ultimately their meaning in relation to the periodicity of large earthquake occurrence such as at Charleston, regional mapping and trenching in selected target areas in the South Carolina Coastal Plain will be necessary, building upon these data already available. Classification as to whether deformations observed are liquefaction-type disturbances (clastic dikes, clay diapirs, tensile hydraulic fractures), indicating that the affected sediment was at or near the sediment/water interface shortly after deposition, or brittle deformations (shear fractures, high angle faults, etc.) indicating that the affected sediments had obtained a certain amount of induration and increased confining pressure (burial) prior to straining. Age relationships based on stratigraphic position, faunal content or direct dating methods will be required.

2) <u>Comparison of contemporary vertical crustal movements to the stratigraphic record near Charleston</u>:

While many investigators have related contemporary vertical crustal movements to the occurrence of seismicity in the continental margin and interior (Bollinger, 1973, 1976: Barosh, 1981; Drake, 1976), few have studied the effects of epeirogency on the stratigraphic record in a systematic fashion. We have been focusing on the resultant (i.e. vertical crustal movements straining the crust with the release of stored energy in the form of earthquakes) rather than the process.

An analysis and comparison of existing and future deep drill data in the Charleston region to contemporary vertical crustal movements (see Figure 1) is necessary to provide insight into the temporal effects of crustal straining in the Charleston area. Establishing a geodata network and releveling of selected first-order leveling lines and their relation to older data (Meade, 1971; Brown & Oliver, 1976) would provide a basis for establishing a comparison to rates of crustal movements deduced from the stratigraphic analysis (i.e., sedimentation rates, presence or absence or thickening or thinning of key stratigraphic horizons). Such an analysis could also provide meaningful information in regard to how the Charleston region measures up to global patterns of epeirogeny at other passive



VERTICAL CRUSTAL MOVEMENT RATES: EASTERN U.S.

(FROM MEADE, 1971)

Figure 1

continental margins. Is Charleston an anomaly or does it fall within some recognizable "mean" pattern?

3) Understanding the state of stress in the crust near Charleston and how it relates to the strain history recorded in the sediments:

While we have intensively studied the Charleston area for some time and have a good knowledge of the stratigraphy, potential field and contemporary seismicity in that region, we must refine and broaden our understanding of the stresses operating in the crust. To do that, multiple deep borehole hydraulic fracturing tests should be conducted in the crust both within and outside the meisoseismal zone of the 1886 Charleston Earthquake. They should be three dimensional, and attempted at as many points in the borehole as possible. Earlier hydrofracturing methods attempted in Charleston had no means of compensating for or detecting any inclination of the stress tensor, as they relied on the assumption that one of the principle stresses was vertical, with the other two horizontal. Methods have been developed where selected pre-existing fractures are isolated by packers and opened with standard pressurizing methods in conjunction with creating new fractures in the standard manner so that a complete three-dimensional stress state can be evaluated.

By understanding the effects of epeirogeny, as reflected in the sediments, and their potential relationship to the rates of crustal straining in the past, it may be possible to make a qualitative correlation of contemporary vertical crustal movements and the magnitude and orientation of stresses operative in the Charleston region.

WHAT IS THE SOURCE OF STRAIN ENERGY IN THE CRUST NEAR CHARLESTON?

As mentioned previously, we need to focus more of our efforts towards understanding processes, rather than the end results. Recent investigators have shown that the presence of stresses in the earth's crust in eastern North Amreica differ considerably from those expected on the sole basis of lithostatic loading alone. These stresses were encountered in rocks ranging in age from Grenvillian to Triassic. The relatively recent deformational structures found in sediments of the Coastal Plain indicate that they are also present in rocks that are as young as Cretaceous Tertiary (Dames & Moore, 1974; Mixon, 1976, Mixon and Mewell, 1976; and York and Oliver, 1976; Wentworth and Mergner-Keefer, 1981; Zoback and Zoback, 1980).

Likewise, these stresses are not restricted to a specific structural setting. They are evident in the gently deformed Paleozoic mollasse basins, in the metamorphic Piedmont, which has undergone significant orogenic deformation, and in the post-orogenic Triassic Basins. Hence, it appears that the observed stress field is a relatively recent phenomenon, at most Mesozoic in age.

The uniform presence of this stress field in rocks of different ages and structural settings indicates that residual or remanent tectonic stress (that is stress remaining in the bedrock from past tectonic episodes) is not a significant component in the existentstress field. The contemporaneity of this field is further substantiated by the demonstrable relationship between the stress field inferred from analyses of phenomena attributed to stress release, such as earthquakes, deformation structures and with in-situ stress measurements.

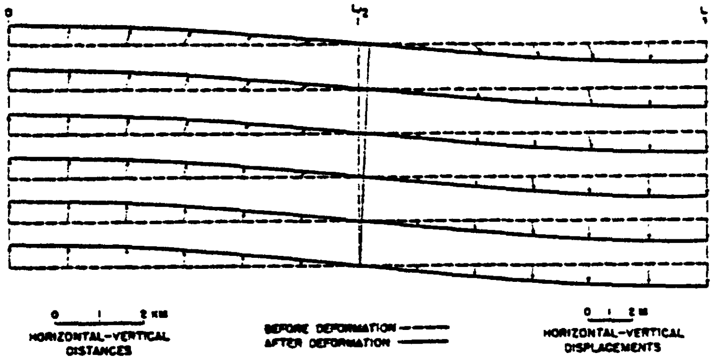
It has been suggested that the present-day stress field within lithospheric plates, including eastern North America, is generated in great part as a response to the driving mechanism of plate tectonics (Voight, 1969; Sbar and Sykes, 1973, 1974; Zoback and Zoback, 1980). The relative motion of a plate with respect to the aesthenosphere would result in a viscous drag at the base of the plate. This drag in combination with the driving push at a spreading center and driving pull at a convergence zone, would constitute the system of forces acting on the lithosphere, including the global intraplate stress field. This stress field would be characterized by nearly horizontal major principal stress vector trending more or less parallel to the spreading direction. In the case of the North American plate, this vector would trend approximately east-west. Computations of intraplate synthetic stress fields based on drag resistance and plate tectonic driving forces are 30^{o} to 80^{o} oblique to inferred stress orientations, (Zoback and Zoback, 1980).

Explaining the origin of the observed stress field on the basis of plate tectonic forces could adequately account for the occurrence of this field in different stratigraphic horizons and various structural settings. It could also account for the relative uniformity of the stress field, which in this paper is considered to be the regional primary field. However, the local pertubations of this field expressed by the occurrence of tensile stresses and local rotations of the stress tensor (as expressed in focal mechanisms and in-situ tests) remain unexplained assuming only lateral plate motions. The presence of these secondary stress fields must therefore indicate the existence of another active crustual process (or processes). It is possible that the origin of these secondary fields is linked, in some way, to recent vertical crustal movements.

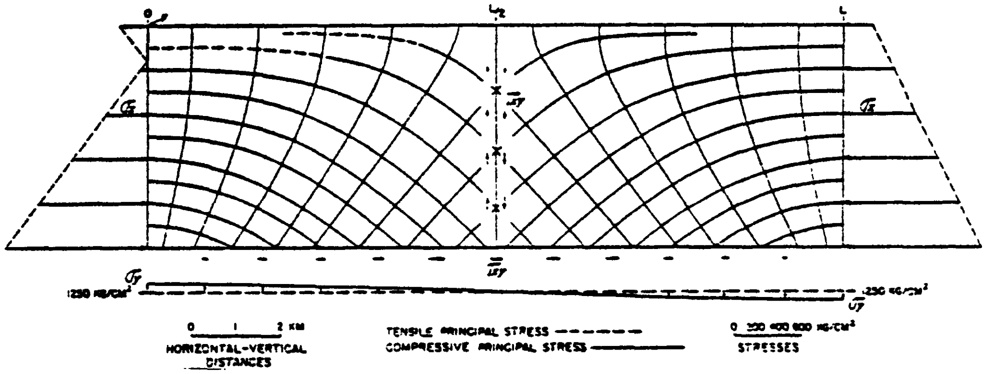
Sandford (1959) studied the two-dimensional system of stresses likely to arise in a block of lithosphere that is subjected to small vertical dislocations (Figure 2). Sandford assumed that the initial horizontal stresses of the surface are equal to zero and that the vertical dislocations are very small and not continuous through time. It was found that a vertical, step-like dislocation causes a differentiation of the stress field across the block such that the horizontal near-surface stress is tensile, whereas in the portion subjected to subsidence, the horizontal near-surface stress is compressional. The boundary zone separating these two areas is characterized by inclined stress trajectories and the occurrence of resolved shear stresses.

Two separate regions of high distortional strain-energy density occur along the upper boundary of the block undergoing a long wave dislocation. These regions are near the crest of maximum uolift and trough of maximum subsidence. As the wave length becomes smaller, a region of high distortional energy develops near the boundary zone between the subsiding and uplifting portions. Bollinger, et. al. (1976) cited this as a possibility for the causes of the Maryville, Tennessee, earthquake sequence in 1973.

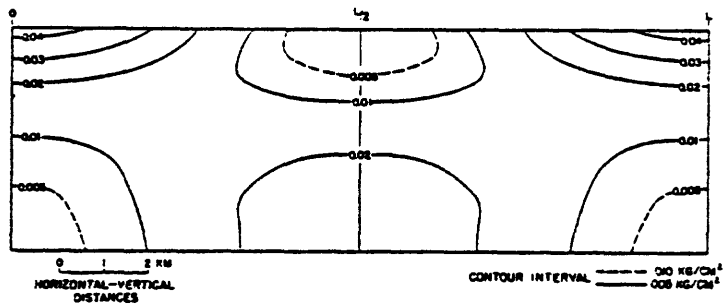
In summary, vertical crustal movements of small magnitude could be of great importance in inducing a significant deflection in the stress field of the lithosphere. These movements could result in the alteration of a pre-existing state of stress and the development of secondary stress fields. They could also account for the occurrence of near surface horizontal tensile stresses, abnormal horizontal compressive stresses and local rotations of the stress matrix. Furthermore, the occurrence of earthquakes and recent deformational structures in the coastal plain sediments could also logically be attributed to vertical crustal movements. We need to understand these relationships better if we are to resolve the Charleston earthquake problem.



Displacement Field



Stress Distribution



Distortional Strain-Energy Density

after Sanford,1959

DAMES & MOORE

Figure 2

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THE EARTHQUAKE THREAT AND ITS MITIGATION IN THE SOUTHEASTERN UNITED STATES

by

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THE EARTHQUAKE THREAT

The human suffering and the property damage which resulted from the 1886 Charleston, South Carolina, earthquake are well documented. This disaster underscored the vulnerability of the area to the hazards of strong earthquakes. With only few exceptions, the majority of buildings, facilities, and lifelines built in Charleston and surrounding areas since 1886 are still without adequate seismic resistance. Accordingly, if a repeat of the 1886 event occurs, the disaster it caused nearly a century ago would be repeated on a magnified scale. The purpose of this contribution to the workshop on "The 1886 Charleston, South Carolina, Earthquake and its Implications for Today" is to address various technical and societal issues and to offer insight into the research needs and action plans required to mitigate the consequences of another severe earthquake.

EARTHQUAKE HAZARD MITIGATION

The solution to the problem of earthquake vulnerability, simply stated, is to incorporate appropriate seismic resistance into buildings, facilities, and lifelines. This process involves a two-pronged approach for the two categories of structures--new and existing.

For new construction, various governmental jurisdictions in the earthquake prone areas need to adopt rational earthquake design criteria. Furthermore, these bodies must develop workable mechanisms to enforce the seismic provisions adopted for use. For earthquake hazard mitigation, especially from the viewpoint of protecting life safety, it is important that some lateral force be included in the design. However, the precise level of this seismic force is somewhat less important. Far more important are the incorporation of proper structural details to provide ample seismic energy absorption without collapse. The level of the seismic loading and, in particular, the sophistication of the design method depend upon the intended use of the facility, concepts which are widely accepted in earthquake resistant design. Therefore, buildings, such as single family dwellings, can develop seismic resistance by adherence to sound structural detailing. Lifelines, on the other hand, should be designed to much stricter standards.

The Uniform Building Code treats the low earthquake frequency area of the Southern United States in the same manner as it does the Western United States That is, current zoning maps are based upon the maximum ground shaking experienced during the available seismic history, without consideration of the frequency of occurrence of these motions. Therefore, it is our belief that the UBC provisions are not directly applicable in the Southeast. Another model code for seismic design, ATC 3-06 (Tentative Provisions) takes into account the low frequency of strong earthquakes in the Southeast. It is also our opinion, however, that these provisions must be evaluated in detail by southeastern and national earthquake engineering experts.

It is most cost-effective to start introducing seismic resistance into <u>all</u> new construction as soon as possible, as opposed to the retrofitting of older buildings. If the next major earthquake does not occur, say, for another 100 years, the Southeast would be essentially earthquake proof, because almost all the buildings and facilities would be (and must be) earthquake designed.

The problem of retrofitting existing buildings, facilities, and lifelines is more difficult and should be studied in great detail. A critical path approach must be implemented. The first priority should be given to those buildings and facilities whose survival would be absolutely necessary for post-earthquake recovery. These facilities should include those offering emergency services, lifelines, etc. The second priority should be given to similar structures which may house a large number of occupants or those in which their mobility is hindered.

The retrofit design standards need not be as exacting as the design criteria for new construction, from points of view involving practicality and the useful remaining life, e.g. the resulting benefit-cost ratio. Advantage should be taken of the opportunities for seismic upgrading when a building is being renovated or refurbished for some other reason. Preservation of historic buildings is a case in point. Perhaps only little additional expenditures would buy significant seismic safety. Federal and State grants for such activities should require seismic provisions.

Finally, intensive short and long-term seismic hazard mitigation activities cannot be sustained with the know-how of personnel imported from other parts of the country. Any set of seismic provisions are only as good as the people who are designing them and the officials who are enforcing them. Major efforts should be taken to educate the professionals in the Southeast. The colleges and universities in the region should become actively involved in earthquake research. These institutions should also teach a variety of relevant subjects to provide a reliable source of trained manpower and to provide a resource center for the local professional community.

ATC 3-06 AND THE SOUTHEASTERN UNITED STATES

The National Science Foundation and the National Bureau of Standards, with participation by a multidisciplinary team of nationally recognized experts in earthquake engineering and allied fields, recently sponsored the preparation of design provisions for seismic design and construction of buildings. These provisions developed under the guidance of the Applied Technology Council, reflect the current state of knowledge in earthquake engineering and incorporate, in a single comprehensive document, modern seismic design philosophies and approaches. The ATC guidelines are currently under evaluation with the direction of the Building Seismic Safety Council, and several such projects, funded by NSF, are underway. The objective of these ongoing efforts is to provide a viable design approach, applicable throughout the United States, to ensure life safety in new and existing buildings.

Several of the features of the Tentative Provisions have been mentioned in the preceding section, as they pertain to the earthquake-prone regions of the Southeastern United States. These concepts are described in more detail, followed by recommendations for specific research activities to address unresolved questions in the application of these provisions in the Southeast.

1) Incorporation of more realistic seismic ground motions.

Building codes in current use do not adequately differentiate between the intensities of ground shaking in the Eastern and Western United States nor do they include the effects of distant earthquakes on long-period buildings. The ATC provisions attempt to alleviate both of these shortcomings via a risk-consistent regionalization of two parameters characterizing the ground motion. The ATC maps provide realistic estimates of ground motion intensities in the Southeastern United States since they account for the lower frequency of occurrence compared with that for Western United States earthquakes. Furthermore, the ATC maps reflect the well-documented differences in rates of attenuation of seismic amplitudes observed throughout the United States

2) a) Classification of buildings into use-group categories or Seismic Hazard Exposure Groups.

   b) Seismic performance for buildings with design and analysis requirements dependent on the Seismicity Index and the Seismic Hazard Exposure Group.

   Seismic performance is a measure of the degree of protection provided for the public and building occupants. The Seismicity Index, related to the intensity of ground shaking, and the Seismic Hazard Exposure Group are used in assigning buildings to Seismic Performance Categories. Analysis requirements depend upon the Seismic Performance Category and building configuration. Other design requirements such as detailing, quality assurance, limitations, and specialized criteria are related to the Seismic Performance Category. It is important to note that the seismic forces do not include a factor which varies for different types of occupancies. This feature reflects the belief that a larger lateral force does not necessarily enhance performance. The improved performance required in critical facilities is provided by design and detailing requirements for the associated Seismic Performance Category and the more restrictive drift limits for the associated Seismic Hazard Exposure Group.

3) a) Guidelines for assessment and systematic abatement of siesmic hazards in existing buildings and

b) Guidelines for assessment of earthquake damage and strengthening or repair of damaged buildings and potential seismic hazards in existing buildings.

The problem of existing buildings is staggering when viewed on a national scale. For example, in metropolitan Los Angeles, the number of buildings of questionable seismic adequacy may exceed 12,000, according to the Committee on Earthquake Engineering Research of the National Academy of Sciences. Of the total number of buildings in the Charleston area, the proportion with inadequate earthquake resistance is greater than in Los Angeles. The provisions embodied in Chapters 13 and 14 of the Tentative Provisions offer guidance in the evaluation and strengthening of existing buildings. These guidelines are of particular relevance for the Charleston area, But they require further study regarding their implementation.

RESEARCH RECOMMENDATIONS

Specific research goals with particular focus on the Southeastern United States should include:

1) Continued studies of source mechanisms and seismic wave propagation in the Southeastern United States. Further research is required to gain knowledge in these subject areas, knowledge which is essential in the interpretation and application of data obtained from our sister Western States.

2) Trial use studies and comparisons with designs using current building codes.

3) Selective research on the identification and assessment of hazardous existing buildings. Particular attention should be focused on unreinforced masonry structures and other vulnerable types of building construction.

4) Developement of methods for reinforcement of existing buildings. Again, attention should be placed on building types of highest vulnerability in the Southeast. Considerations of the preservation of historical significance should be included where applicable.

ASPECTS OF L_g GROUND MOTION IN THE COASTAL PLAIN REGION

by

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INTRODUCTION

Both time domain and spectral analysis of short-period, three-component data on L_g in the Eastern United States show unusually large regional variations in the ratio of the largest horizontal (H) to the largest vertical (Z) component of ground motion. The ratio H/Z is significantly larger than 2 for the Coastal Plain region in which Charleston, South Carolina is located. Estimates of design ground motions for sites in the Eastern United States are generally based on the excitation level of L_g derived mainly from analysis of vertical component data. To obtain the horizontal component of ground motion from the vertical component, the usual procedure is to assume the horizontal motion to be twice as large as the vertical. According to the standard design response spectra in the Nuclear Regulatory Guide 1.60, based on strong motion data recorded mostly in the Western United States, the ratio of the horizontal to the vertical component is dependent on frequency but no greater than 1.5. It seems therefore that the use of H/Z equal to or less than 2 will underestimate the expected ground motions at sites in the Coastal Plain region.

TIME DOMAIN RESULTS

A statistical analysis of a fairly large amount of three-component data on L_g at LRSM stations in the Eastern United States was recently carried out by Gupta et al. (1982). Large regional variations in the ratio of the largest horizontal (H) to the largest vertical (Z) component of ground motion were found. Mean values of the ratio H/Z for the 31 LRSM stations used in that study are shown in Figure 1 (after Figure 3, Gupta et al., 1982). The large regional variations indicate that the assumption of H/Z = 2 for all sites in

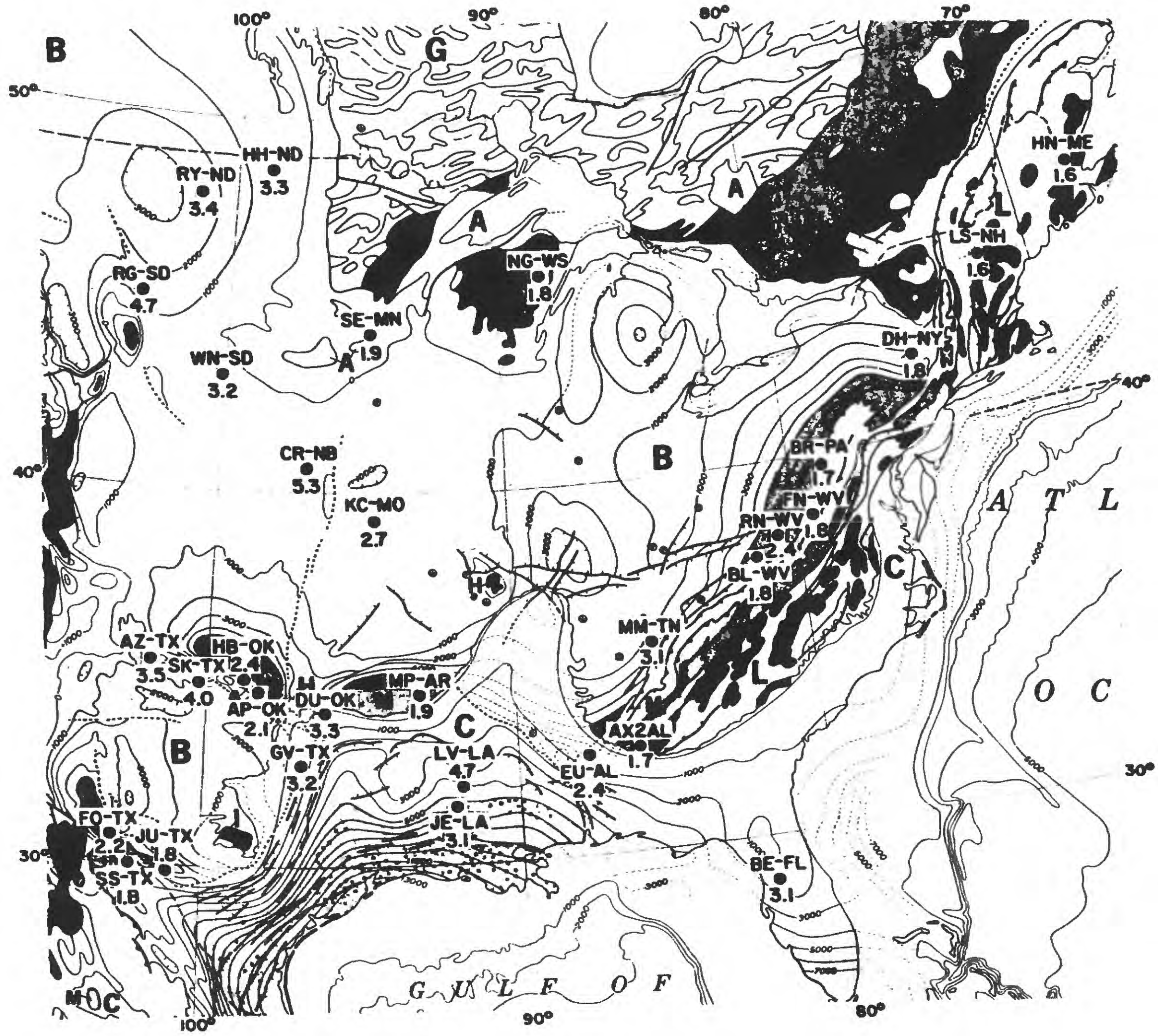

Figure 1. Mean values of horizontal to vertical L amplitude ratio, H/Zfor 31 LRSM stations with locations shown on a generalized tectonic map of North America (after Figure 3, Gupta et al., 1982).

the Eastern United States is not valid. Sites in the Coastal Plain region have large values of H/Z whereas those in the Appalachian Mountains region generally have the smallest values of H/Z. The largest values of H/Z belong to sites in the platform region of the Central United States. As already discussed in Gupta et al.(1982), there is an indication that values of H/Z may significantly influence the local earthhquake intensity due to a large earthquake. The "earthquake shadow" over southern Pennsylvania, West Virginia, and northeastern Virginia, where a marked reduction in the intensity of ground motion was observed (Dutton, 1886), could, at least in part, be due to anomalously low values of H/Z in this region. Additional data from several other earthquakes will, of course, need to be examined to explore this possibility.

In a region with low velocity overburden, large values of the ratio H/Z are expected for shear waves including L_g (Gupta et al., 1982). It is interesting to note that a recent study of three-component strong-motion array data from earthquakes in Taiwan showed the peak acceleration of horizontal components to be, on average, three times that of the vertical component (Bolt et al., 1982). Seismic surveys in this region indicate a "surficial layer of recent alluvium with P wave velocities of 500 to 1000 m/s overlying Pleistocene rock with P wave velocities of 1800 to 2000 m/s" (p. 571, Bolt et al., 1982). These velocities are typical of low velocity overburden so that Gupta et al.'s (1982) results not only explain the Taiwan data but also suggest their applicability to strong-motion data in which the largest-amplitude phase is not the conventional L_g phase.

SPECTRAL ANALYSIS OF THREE-COMPONENT L_g

The three-component short-period LRSM analog records of several earthquakes with good recordings of the L_g phase were digitized and the two horizontal components rotated so that the vertical (Z), radial (R) and transverse (T) components could be obtained. The digitizing rate was 20 samples per second which corresponds to the Nyquist frequency of 10 Hz. Time windows for the L_g phase, selected to be the same for the three components, were tapered with a Parzen window and Fourier transformed. The power spectrum was corrected for instrument response and smoothing over a variable number of spectral amplitudes was applied. The noise spectra were obtained in exactly similar manner by using a time window before the onset of the P phase. Power in noise was subtracted from the power in observed signal for each component before the displacement spectral ratios R/Z, Z/T and R/T were obtained.

On the basis of the time-domain results, one may classify the locations of most LRSM sites used in this study into three distinct categories: (a) Hard Rock Sites such as BL-WV and BR-PA; (b) Sites with low velocity overburden or 'Soft Rock' sites, such as EU-AL and JE-LA; and (c) Sites within the central stable region such as CR-NB and KC-MO. Component spectral ratios were obtained for a few sites in each of the three categories. The L_g windows, used in the spectra, were 25.6sec long on each component and began with a group velocity of about 3.5 km/sec. They generally contained the largest-amplitude arrivals or most of the energy in the L_g wavetrain. In general, there was good agreement between the time-domain value of H/Z and the frequency-domain value for the frequency range of about 1 to 3 Hz. Typical component spectral ratios for the site EU-AL in the Coastal Plain region (see Figure 1 for its location) are shown in Figure 2. These results are from the Alabama earthquake of 18 February 1964 (m_b = 4.2) for which the epicentral distance to EU-AL is 314 km.

The general behavior of component spectral ratios can be explained in terms of the influence of scattering on L_g (Gupta and Blandford, 1983). Progressively more scattering with increasing source-receiver distance leads to continuous interaction among the three orthogonal components of ground motion, via scattering processes, SV$\rightarrow$SH and SH$\rightarrow$SV. The result is nearly isotropically polarized shear waves trapped within the crust and incident on the Moho at large angles of incidence. As these shear waves propagate upwards towards the receiver, they are modified by the local structure of the recording station. The effect of the free surface, where observations are generally made, is to make the observed transverse component larger than either of the other two orthogonal components. Application of Haskell's (1960, 1962) methods for computing surface displacement due to propagation of SH and SV waves through plane stratified media to the local structure at EU-AL (see Figure 13, Gupta and Blandford, 1983), leads to component spectral ratios in good agreement with those in Figure 2. Note that the data in Figure 2 indicate H/Z to be generally increasing with frequency; it is about 3 at low frequencies around 2 Hz and about 5 at high frequenciesof about 8 Hz.

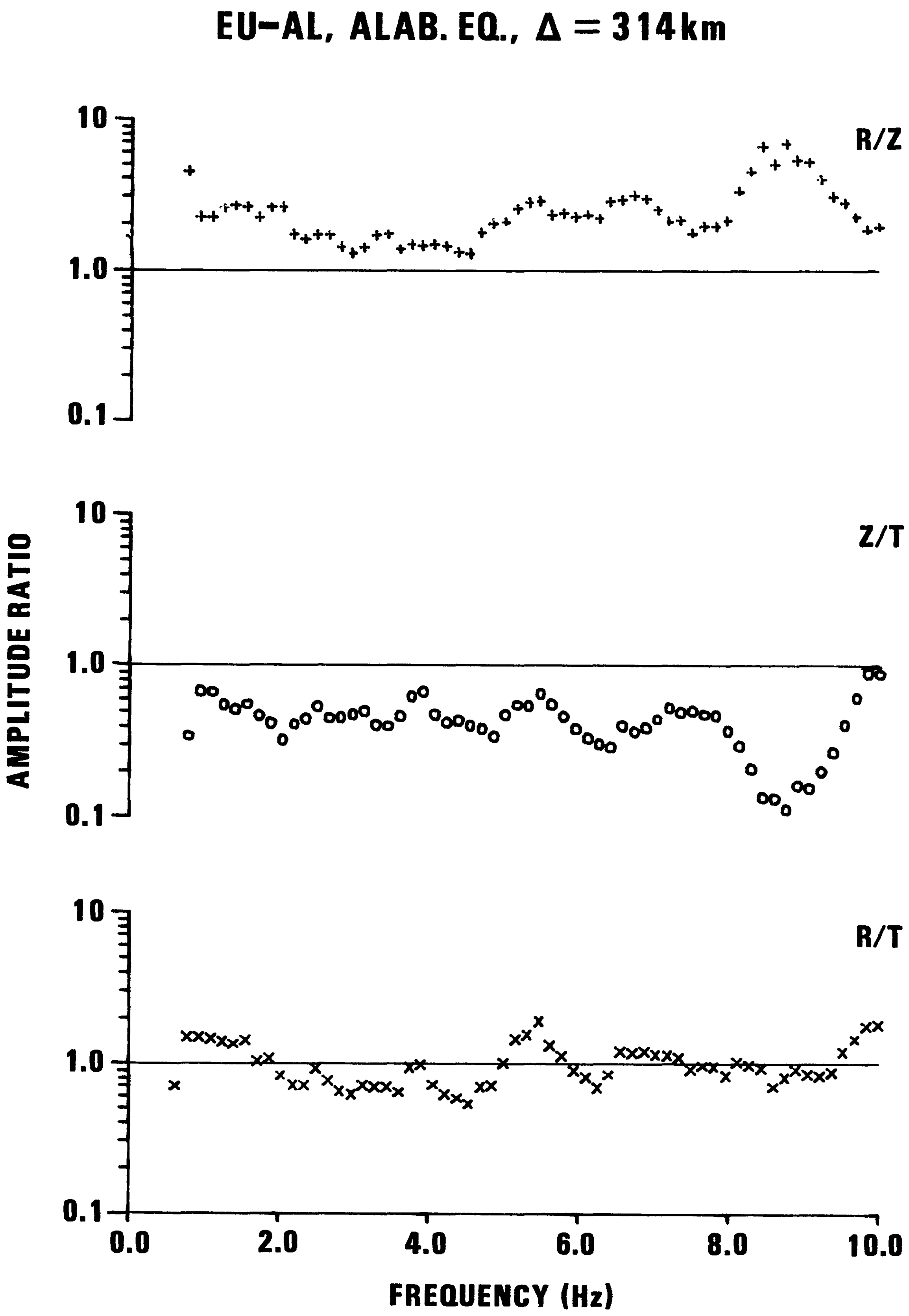

Figure 2. Component spectral ratios of L observed at EU-AL from the Alabama earthquake of 18 February 1964.

DISCUSSION AND CONCLUSION

Both time-domain and frequency-domain results, based on three-component short-period L_g, demonstrate the strong influence of scattering, especially for large epicentral distances and/or higher frequencies. The ratio of the largest horizontal to the largest vertical component or H/Z is significantly greater than 2 for several regions in the Eastern United States. This ratio is likely to be substantially greater than 2 in the Atlantic Coastal Plain region that contains the epicentral region of the 1886 Charleston earthquake although an accurate value of H/Z for this region could not be obtained due to the lack of a suitable LRSM station. Detailed studies of L_g propagation in this region will be necessary to obtain more accurate, site-specific estimates of maximum horizontal motion. Similarly, the possibility of H/Z increasing with frequency, as suggested by Figure 2, needs to be confirmed by further studies. It should be noted that frequencies up to at least 10 Hz are important in earthquake engineering. It seems therefore that the standard response spectra, specified in the Nuclear Regulatory Guide 1.60, need to be significantly modified for application to areas such as the Coastal Plain region of the Eastern United States.

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SEISMIC DESIGN REQUIREMENTS IN THE SOUTHEASTERN UNITED STATES

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INTRODUCTION

Seismic risk varies throughout the entire United States and throughout the Southeastern States. Seismic design criteria frequently use zone maps such as the one in Figure 1 as a measure of risk. The seismic risk is smallest for zone zero and largest for zone 4. The design criteria do not change within a zone. That is, a zone two in South Carolina is treated the same as a zone two in Mississippi, New York, or California. Accordingly, the discussion in this paper is not necessarily limited to the Southeastern States.

The majority of the construction in the United States is undertaken by the private sector and regulated by local government. These local regulations are, in turn, based largely on provisions of one of the three model building codes and/or voluntary national standards. Regulations for Federal buildings tend to be similar to the model codes and national standards, and in some instances, defer to local requirements. This chapter discusses seismic requirements of the model codes, national standards, and Federal requirements. It also discusses some of the source material for the various provisons.

STRUCTURAL ENGINEERS ASSOCIATION OF CALIFORNIA (SEAOC)

The report "Recommended Lateral Force Requirements and Commentary" (Structural Engineers Association of California, 1974) contains requirements which:

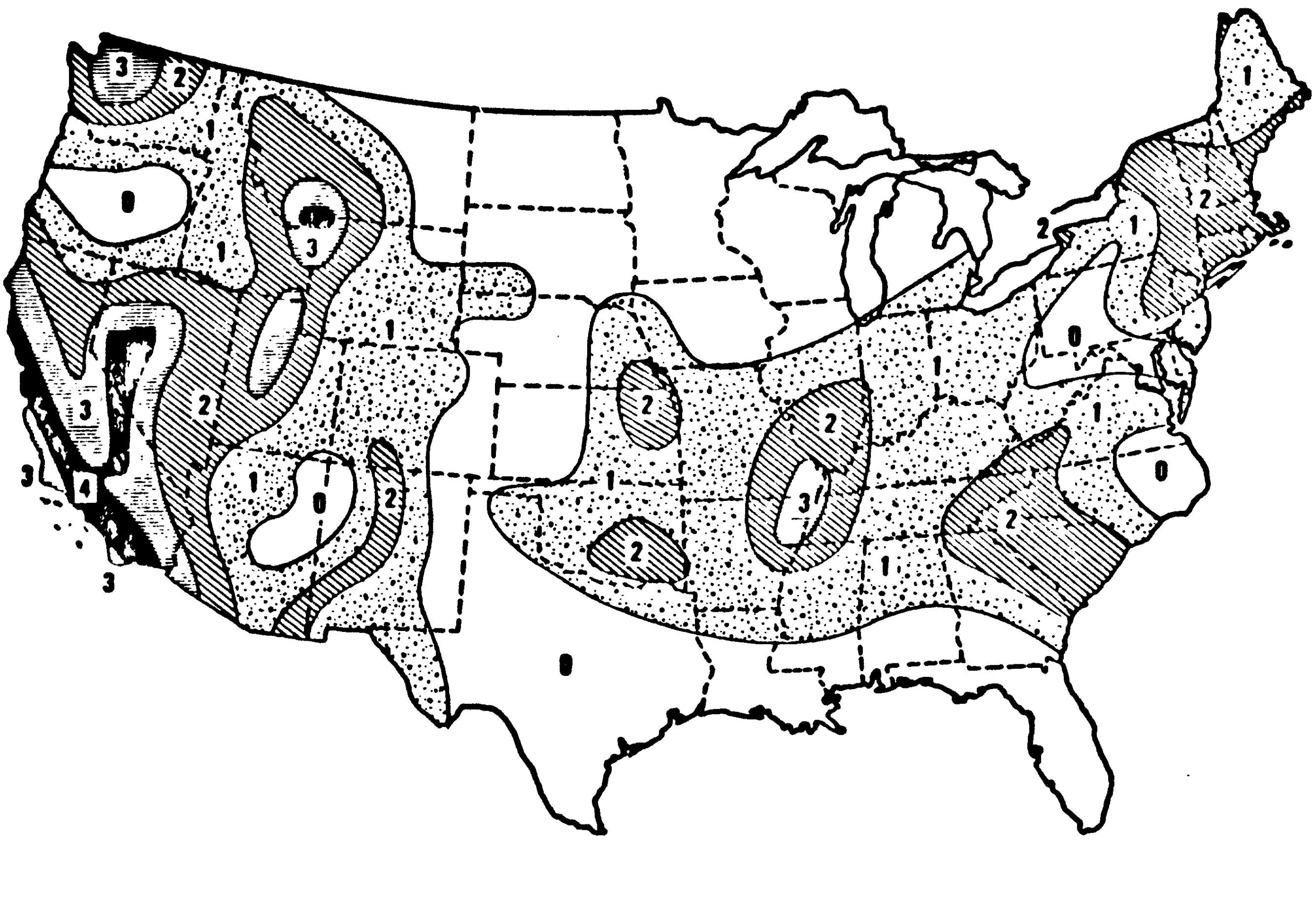

Figure 1.--Seismic risk zone map used by ANSI A58.1-1982

"are intended to provide criteria to fulfill life safety concepts. It is emphasized that the recommended design levels are not directly comparable to recorded or estimated peak ground accelerations from earthquakes. They are, however, related to the effective peak accelerations to be expected in seismic events. More specifically with regard to earthquakes, structures designed in conformance with the provisions and principles set forth therein should, in general, be able to:

1. Resist minor earthquakes without damage;

2. Resist moderate earthquakes without structural damage, but with some nonstructural damage;

3. Resist major earthquakes, of the intensity of severity of the strongest experienced in California, without collapse, but with some structural as well as nonstructural damage.

In most structures it is expected that structural damage, even in a major earthquake, could be limited to repairable damage. This, however, depends upon a number of factors, including the type of construction selected for the structure."

Most current seismic design criteria can be traced to the SEAOC recommendations. Inherent in this design approach is the acceptance of inelastic behavior of the building structure. Some damage is anticipated although the extent depends on the magnitude of the earthquake. Although this is the normal philosophy for building design, it might not be acceptable in all instances. Buildings which must remain functional following an earthquake, such as hospitals, require extra consideration.

The following description of the technical requirements of the SEAOC recommendations is similar to that given by Forell (Forell, 1981). The basic design procedure involves determination of an equivalent static base shear which is applied to the structure in a specified manner. The design formula for the base shear, V = ZIKSCW, takes into consideration the seismicity of the area (Z), the importance of the structure (I), the type of the lateral resisting system (K), the response of the structure (C), which is related to its fundamental period of vibration, the site structure interaction (S), and the effective inertial mass of the structure (W). The recommendations have provisions for the vertical and horizontal distribution of the base shear force that take into consideration the higher modes of vibration in the vertical distribution, torsional forces due to eccentricities, and overturning. Limitations are also placed on allowable drift. The recommendations cover performance of structural systems by establishing minimum limits of ductility, deformation, compatibility, and special detailing requirements. Specific requirements are included for concrete ductile moment-resisting space frames, concrete shear walls and braced frames, and steel ductile moment resisting space frames.

It should be noted in the formula for computation of base shear that the coefficient Z varies to reflect the seismicity of the region (zone) in which the building is being designed. The SEAOC criteria do not contain specific recommendations for values of Z other than a value of 1.0 for areas of highest seismicity. Other design criteria do contain recommendations for Z which depend on the seismic zone obtained from a zone map (see Table 1). These recommendations are discussed later for the specific criteria.

The factor I varies between 1 and 1.5 depending upon the functions of the structure. A building such as a hospital has an importance factor of 1.5.

Many typical buildings can be designed using a static analysis approach. Although a dynamic analysis may be required in some instances, its primary benefit is to determine a better distribution of forces on the building rather than to alter the total base shear.

APPLIED TECHNOLOGY COUNCIL (ATC)

A recent major resource document is the "Tentative Provisions for the Development of Seismic Regulations for Buildings" (prepared by the Applied Technology Council, published by the National Bureau of Standards and

Table 1. Z Coefficients

Design Criteria/Seismic Zone	0	1	2	3	4
SEAOC Z-Factor*	-	-	-	-	1
ANSI Z-Factor	0	3/16	3/8	3/4	1
UBC Z-Factor	0	3/16	3/8	3/4	1
Tri-Service Z-Factor	0	3/16	3/8	3/4	1

*SEAOC refers only to a Z-factor of 1 for the highest seismic risk area.

subsequently referred to as the ATC Provisions). This report was published in 1978 as a state-of-the-art document for seismic design.

The ATC Provisions, like the SEAOC criteria, involve computation of a total base shear which is then distributed on the structure in a prescribed manner. However, the equations for computation of the base shear and the distribution of the base shear are different from SEAOC. The base shear formula $V = C_s W$ is a function of the seismic design coefficient (C_s) and the effective inertial mass of the structure (W). Two equations are provided for computation of the coefficient C_s. Although the two equations are different, both of them involve use of a response modification factor that is a function of the construction type and material and a factor representing the seismic intensity.

The response modification factor serves a purpose similar to the K factor in the SEAOC criteria. It varies according to the lateral load resisting system and is selected to allow inelastic behavior similar to that allowed by SEAOC.

Two maps are provided for determination of the seismic intensity factor, one in terms of effective peak acceleration and the second in terms of effective peak velocity-related acceleration. Each map is divided into seven map areas (the larger the number the higher the risk), the effective peak velocity-related acceleration map is shown in Figure 2. The map areas are defined by county lines in an effort to simplify difficulties associated with crossing of political boundaries. Since the map areas are based on accelerations, which in turn provide the basis for the lateral force equations, the design base shear is related to realistic ground motion intensities. It should be noted that these map areas do not correspond to the zone map used to determine the Z factor. They can, however, be related as in Table 2. The numbers are also not directly related to other measures of intensity such as the Modified Mercalli scale.

The ATC Provisions do not use an importance factor to account for the occupancy or critical nature of a building. Instead, the Provisions divide buildings into three Seismic Hazard Exposure Groups which consider these factors. A building is rated as falling into a specific exposure group

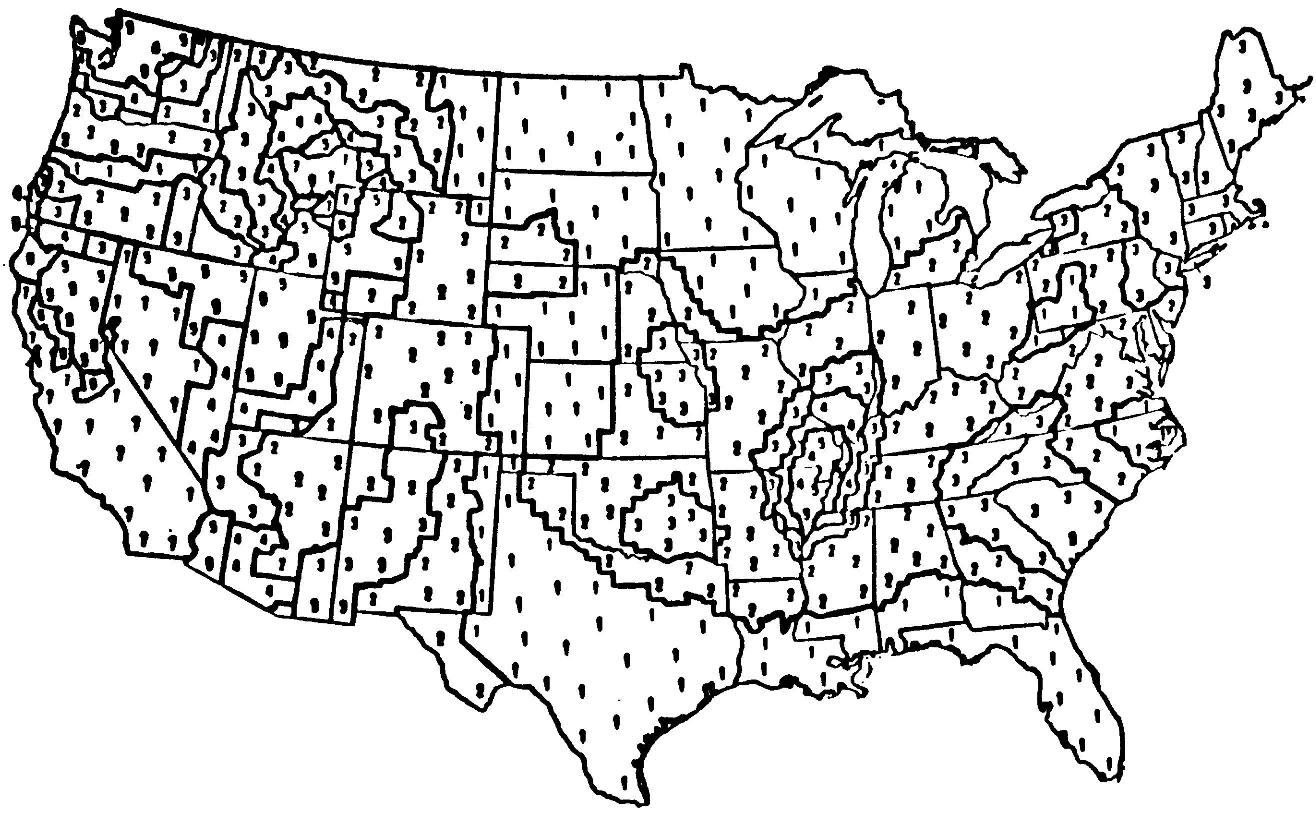

Figure 2. ATC map areas based on effective peak velocity-related acceleration.

Table 2. Approximate Relation of ANSI Zones with ATC Map Areas (ANSI A58.1)

ATC Map Areas	ANSI Map Zones
7	4
5,6	3
3,4	2
2	1
1	0

depending on its use and this rating is combined with a Seismicity Index, which is dependent upon the seismic map area, and used to determine a Seismic Performance Category applicable for the structure. The Seismic Performance Category then spells out design and detailing requirements. The more important a structure and the higher the seismicity, the more stringent the design and detailing requirements.

The report with amendments (National Bureau of Standards, 1982) is being evaluated by the Building Seismic Safety Council in a national trial design program (National Bureau of Standards, 1982). It is anticipated that the Building Seismic Safety Council will publish revised provisions following the conclusion of the trial design program.

NATIONAL STANDARDS

The American National Standards Institute publishes the ANSI A58.1-1982 "Minimum Design Loads for Buildings and Other Structures" (American National Standards Institute, 1982), the only voluntary national loading standard in the United States. The Standard contains requirements for earthquake loads that are suitable for inclusion in building codes and other design documents. The earthquake load requirements as is the case for other design approaches consider that inelastic behavior of the building will occur. Accordingly, earthquake design requires knowledge of the material behavior as well as the applied loads. Since the ANSI Standard is a loads document, it provides limited guidance on material behavior. Other national standards such as that published by the American Concrete Institute (American Concrete Institute, 1977) for reinforced concrete design, must be selected for the specific material type. The seismic design requirements contained in ANSI A58.1-1982 are similar to those contained in the SEAOC recommendations and in the Uniform Building Code (International Conference of Building Officials, 1982) and parts of the report "Tentative Provisions for the Development of Seismic Regulations for Buildings" (Applied Technology Council, 1978). The seismic risk map used in the ANSI A58.1-1982 Standard is based on work performed in developing the ATC Provisions. Specifically, the information used in developing the ATC map in Figure 2, was used in developing the ANSI map shown in Figure 1. In order to maintain consistency with current earthquake design practice, the map was divided into zones 0-4 for purposes of selection of the zone coefficient Z. The Z coefficients are shown in Table 1.

MODEL CODES

There are three model codes in the United States. These are the model codes published by the International Conference of Building Officials - Uniform Building Code; Building Officials and Code Administrators International, Inc. - Basic Building Code; and Southern Building Code Congress International, Inc. - Standard Building Code. The Basic Building Code and the Standard Building Code contain seismic provisions that are based on the ANSI A58 Standard. However, the 1972 edition is referenced rather than the more recent 1982 edition. There are a number of differences between the two editions of the ANSI Standard. A major difference is the map in the 1982 edition which is based upon risk while the 1972 edition uses a map based on information available in 1968 on the maximum size earthquake. The equation for base shear in the 1982 edition also includes the importance factor, I, which was not used in the earlier version.

The Uniform Building Code (UBC) contains seismic design requirements which, for the most part, are based upon the recommendations of the Structural Engineers Association of California. The base shear equation used in the UBC is essentially the same as that used in the SEAOC recommendations and in the ANSI Standard. However, the zone map used in the UBC is based upon the maximum earthquake which has occurred in a region and thus has different boundaries from the map used by ANSI. This zone map is shown in Figure 3. The principal difference between the two maps is to reduce the required Z factor (used in computing base shear) for many areas, particularly in the Eastern portion of the United States Other differences exist but are not discussed here.

The report "Directory of State Building Codes and Regulations" (National Conference of States on Building Codes and Standards, Inc., 1982) documents general use of codes within the states. According to that report the code requirements in the Southeast are based primarily on the Standard Building Code. It should be noted that there are differences between states and within states.

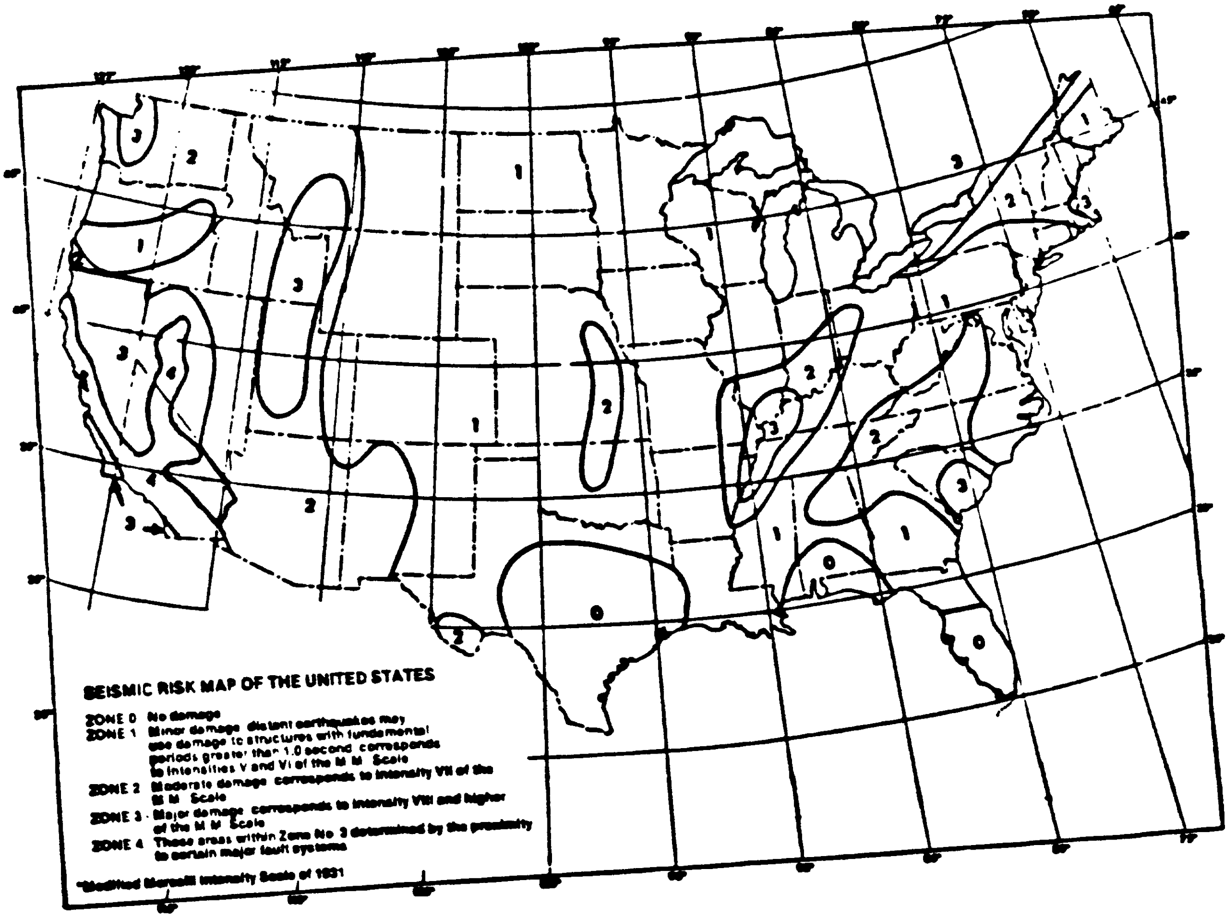

Figure 3.--Seismic risk zone map used by the Uniform Building Code

FEDERAL CRITERIA

Federal criteria for building design vary from agency to agency. Some agencies reference local codes while others have their own provisions.

The Army, Navy, and Air Force manual "Seismic Design for Buildings" (U.S. Government Printing Office, 1982) is commonly referred to as the Tri-Service Manual. It governs design and construction of Armv, Navy, and Air Force facilities. The 1982 edition supersedes the 1973 edition. This manual contains specific guidelines for procedures and details that facilitate implementation of provisions for seismic resistance of buildings. The manual is based on the recommendations of the Structural Engineers Association of California discussed earlier. Additionally, it contains extensive design examples and illustrations of use of the guidelines. The seismic zone map used to select the Z factor is shown in Figure 4.

The Veterans Administration has design requirements (Veterans Administration, 1974) which use somewhat different design procedures from the Uniform Building Code but give design results similar to the UBC. The VA design requirements include the necessity to conduct a site evaluation for each VA hospital instead of using a zone map.

The General Services Administration (GSA) has published guidelines for design of buildings although the GSA usually defers to local building codes. Current practice in other Federal agencies, particularly those with grant or lease programs, is to use design which conforms to the local building code.

EXISTING BUILDINGS

Retrofit of existing building to conform with newer seismic design requirements varies from Federal agency to agency. The Veterans Administration has required evaluation of all of its hospital structures and when necessary, they are upgraded to conform to its newer design requirements. The military services are undergoing a program of identification of existing structures requiring strengthening and a program of strengthening when necessary.

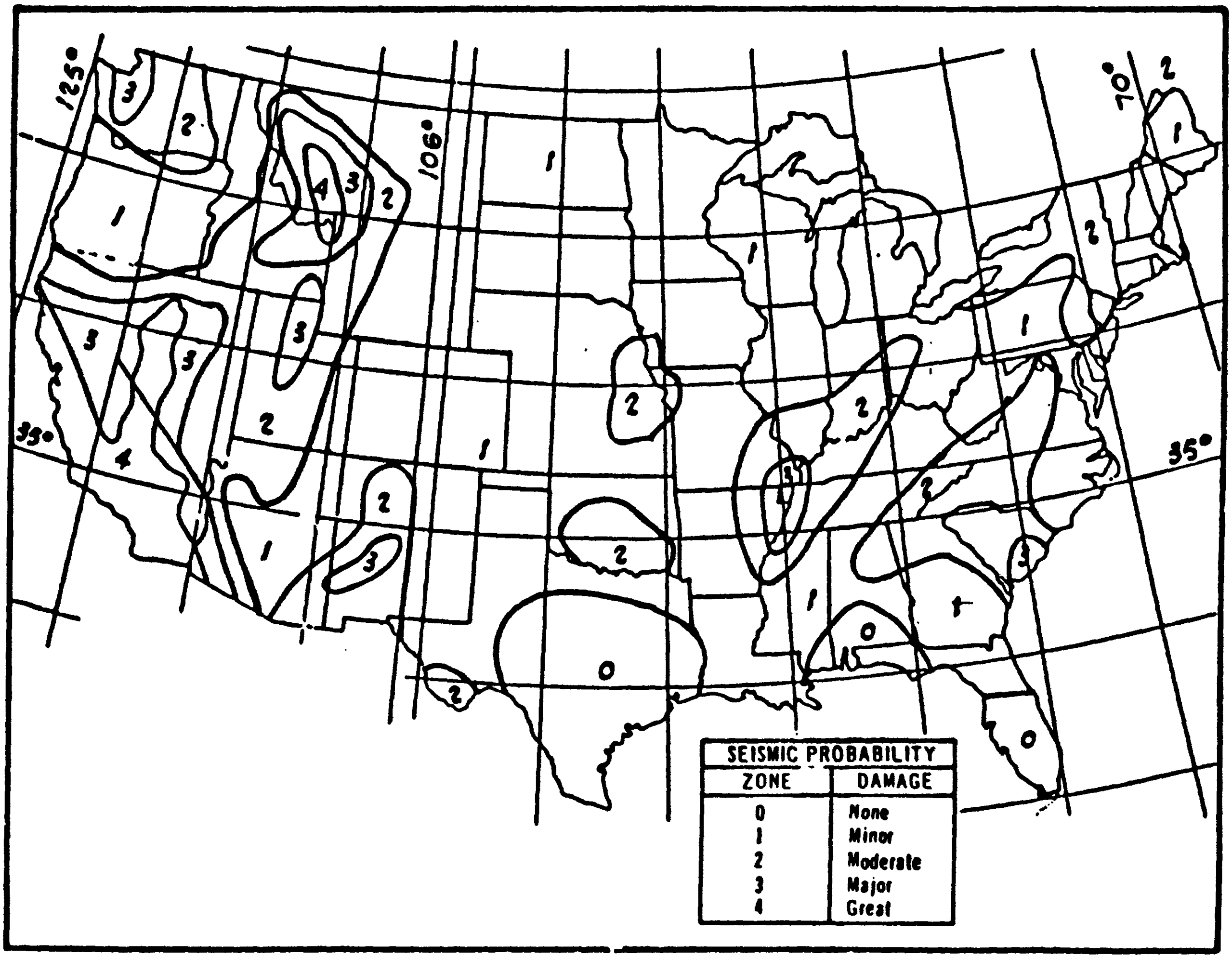

Figure 4.--Seismic zone map used by the Tri-Service Manual.

SUMMARY

The earthquake design requirements contained in national standards, model codes, and Federal design requirements have been described. In the Southeastern United States the building codes are based primarily on the Standard Building Code which has seismic provisions based on ANSI A58.1-1972 "Minimum Design Loads for Buildings and Other Structures."

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THE CHANGING TECTONIC BASIS FOR REGULATORY TREATMENT OF THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE IN THE DESIGN OF POWER REACTORS

by

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INTRODUCTION

A key element in the design criteria for nuclear power reactors is the seismic loading that must be accommodated by the reactor structure and its contained equipment. The intensity X (MM) earthquake that occurred near Charleston, South Carolina, in 1886 is by far the largest earthquake experienced along the eastern seaboard in the 300 years of historic time. Depending on the neotectonic coherence of the eastern seaboard, this large earthquake may represent the earthquake potential of most of the region or of only the Charleston area. The difference can be important, because inclusion of an MM X earthquake in the suite of earthquakes that must be considered would lead to significantly higher design values than otherwise.

Decision of how to treat the occurrence of earthquakes in design of civilian power reactors lies ultimately with the U.S. Nuclear Regulatory Commission (NRC)--earlier the U.S. Atomic Energy Commission (AEC)--which has regulatory responsibility to assure the health and safety of the public. A careful effort is made to found the regulatory decisions on the best information available when decisions must be made.

When civilian power reactors began to be proposed along the eastern seaboard in the early 1960's, very little was known about the origin of the Charleston, South Carolina, earthquake or about eastern earthquakes in general. Nevertheless, decisions had to be made. Since then, much has been learned about the tectonics of the Charleston, South Carolina, area and the eastern seaboard, although the 1886 earthquake is not yet well understood. The base of tectonic information available for regulatory decision is quite different today than it was 20 years ago, and further improvements can be anticipated.

This essay is based on my own experience with reactor licensing and eastern tectonics, the technical literature, and conversations over the years with various scientists involved in eastern work and Geological Survey advice to the NRC. The pertinent technical literature is included or cited elsewhere in this volume or in the two USGS volumes on the Charleston earthquake, Professional Papers 1028 and 1313. The summary of research results presented here highlights selected points to illustrate the change in our understanding of the Charleston earthquake and its regional setting but is not a thorough review of all relevant work.

INTERPLAY BETWEEN SCIENCE AND REGULATION

The inherent differences between science and regulation create unavoidable problems for regulation. The regulatory process seeks a stable basis for decisions that will be incorporated in engineering designs and constructed reactor plants. Science, however, proceeds onward, challenging today's views and seeking a better understanding of nature through further research and hypothesis testing. Once initial regulatory decisions have been made, significant changes in our understanding of earthquake tectonics could lead to shifting design requirements or even compromise of existing safety factors in constructed plants. Design changes are costly and modification of existing plants to meet higher seismic standards, where possible at all, would be even more expensive. Where limited knowledge has led to very conservative regulatory positions, improved understanding of earthquake hazard might permit more realistic, less expensive design requirements.

The uncertainty and progressive change inherent in science, especially as it applies to such a poorly understood phenomenon as eastern earthquakes, necessarily conflicts with the ideal requirement of an adequate and stable basis for reactor design and construction. In the long run, however, improvements in knowledge are imperative, and regulation must accommodate change. Where a faster pace or focussed judgments in the relevant science are needed, regulation can help pose the critical questions and stimulate progress by fostering increased funding for the needed research.

RESTRICTION OF LARGE EARTHQUAKES TO CHARLESTON

Little more was known about the Charleston earthquake in the early 1960's than in the years immediately following 1886. The earthquake occurred in the evening on the last day of August, centered slightly northwest of Charleston, South Carolina, in a region of low, swampy ground. It lasted less than a minute, claimed 60 to 100 lives, caused extensive damage in Charleston and the surrounding region, and was felt 1200 km away in Chicago. Sloan and Dutton documented damage of man-made structures and liquefaction of surficial sediments but found no evidence of surface faulting. They defined the 30 x 50 km area of most severe effects (meizoseismal area) and assigned the earthquake a maximum intensity of Rossi-Forel X.

Many earthquakes have occurred in the east in historic time, but most have been located within a broad northeast-trending band that passes well west of the Charleston area. The 1886 shock and the hundreds of subsequent earthquakes that were assigned to the Charleston epicentral area occurred in a coastal region otherwise largely free of historic seismicity. Not only was the Charleston earthquake thus unusual in its location, it was unusually large. It was considered an intensity IX or X earthquake on the modified Mercalli scale, whereas the largest earthquake elsewhere along the eastern seaboard did not exceed MM VIII.

The meizoseismal area of the 1886 earthquake lay near the coast where nearly a kilometer of Coastal Plain sediments overlay basement. The Coastal Plain sediments were known to be warped on a regional scale into broad arches and embayments but were otherwise considered undeformed. The shape of the basement surface was crudely known, and Charleston lay on the northern flank of the Southeast Georgia embayment. The underlying basement was assessed to be an eastward subsurface continuation of the Paleozoic metamorphic rocks exposed in the Piedmont to the west, although the magnetic field in the Charleston area was recognized to be somewhat unusual.

Based on these sparse facts, the AEC determined that any recurrence of an earthquake as large as the 1886 event along the eastern seaboard would be confined to the Charleston area. The seismic design of power reactors in that area would be controlled by the Charleston event. Elsewhere along the eastern seaboard, however, the seimic design of reactors would be controlled by smaller events representing the largest in the local area. Once this decision was made and incorporated in engineering designs and constructed reactors, the practical burden of proof lay on any argument that Charleston-size earthquakes could occur elsewhere along the eastern seaboard.

RESEARCH PROGRESS

Expanded research funding that began in the mid 1970's focussed considerable scientific attention on eastern earthquake problems. This expansion was stimulated by concern about the poor information base for regulatory decisions and to a lesser extent about the direct earthquake hazard to society. The NRC sponsored work directed at identifying the tectonic structure responsible for the 1886 Charleston earthquake. It also provided major support for the northeast seismic network. The Geological Survey supported study of the regional context of the 1886 earthquake, particularly Cenozoic faults in the southeast and the means to date them. The newly created National Earthquake Hazards Reduction Program supported some work on eastern earthquakes, and utility-sponsored studies made contributions. Concurrently, an extensive marine geology program was exploring the Atlantic shelf and slope offshore. Of this effort, the federal investment in understanding the Charleston earthquake and its setting has been on the order of a million dollars a year for the past ten years, which is a very modest investment given the importance of the issue.

Progress was particularly enhanced by two fundamental advances. Plate tectonics, the great integrating paradigm in geology whose influence now permeates all tectonic work, was barely nascent in the early 1960's. Secondly, the development of high-speed computers has permitted the use of multifold seismic-reflection profiling, which has revolutionized the study of subsurface structure.

Charleston Seismicity

Analysis of intensity data indicates that the 1886 main shock had a maximum intensity of MM X and a magnitude of about 7. The source dimensions are estimated for a steep fault as a fault length of 20-30 km, a width of 12 km, and an average slip of 1 m. Alternatively, it has been proposed that the main shock had a subhorizontal source with an area nearly as large as the Coastal Plain portion of South Carolina.

A seismic network installed in South Carolina and concentrated on the 1886 meizoseismal area has recorded about 50 earthquakes, the largest of magnitude 3.7. Most of these earthquakes are clustered in the western half of the 1886 meizoseismal area and occur within the upper crust (depths of 3-15 km). Focal mechanisms are still controversial, although a subhorizontal compression axis in the northeast quadrant seems indicated. No simple fault plane is defined by the hypocenters in three dimensions. The epicenters of this contemporary seismicity in South Carolina do not form a continuous northwest alinement, although the two main clusters do lie on such a trend. Relocation of earlier instrumentally recorded earthquakes makes them compatible with these clusters.

Study of historic seismicity suggests that, for the 15 years prior to the 1886 event, a crude perimeter of earthquakes near the margins of coastal South Carolina enclosed an aseismic area 350 km in diameter. After the main shock, hundreds of earthquakes, most newly discovered through study of contemporary newspapers, seem to have filled in the aseismic hole. Previous assignment of all 1886 aftershocks to the meizoseismal area seems to have been in error.

Structure in the Charleston Area

The Coastal Plain wedge of sedimentary rocks in the Charleston area has been demonstrated--through surface mapping and shallow and deep drilling--to be 750 m thick and to consist of 500 m of Cretaceous overlain by 250 m of lower Tertiary strata. Upper Cenozoic sediments that might record recent tectonic deformation are poorly represented, although Quaternary shoreline deposits mantle the surface. The Coastal Plain strata are nearly horizontal and contain no recognizable faults in the shallow section, although irregular unconformities limit the resolution of this constraint.

Beneath the Coastal Plain section, deep drilling has revealed 250 m of subaerial basalt flows that petrologic and geochemical studies and seismic refraction and reflection suggest represent a buried flood-basalt field at least 100,000 km^2 in area. A radiometric age of 184 m.y. indicates formation of the basalts soon after the rifting of the continent that initiated Atlantic opening.

The surface of these basalts is nearly undeformed. Like the overlying sediments, it is almost flat lying and is not broken by faults having large vertical offsets. The basalt surface is broken locally, however, by faults having vertical offsets of 50 m or less. Seismic reflection profiles indicate that some of these faults penetrate up into the lower Tertiary strata with progressively smaller offsets that become lost in the complicated shallow stratigraphy. Correlation between reflection lines suggest the faults have northeast strikes.

Unconformable beneath the flood basalts, major horst-and-graben structure is indicated by seismic refraction and the presence of sedimentary redbeds sampled by the drill. Like the early Mesozoic extensional structure exposed in the Piedmont and inferred on and offshore beneath the sedimentary cover from aeromagnetics, these structures trend northeastward.

Structure within the pre-Triassic basement is still poorly known, but includes some shallow mafic plutons inferred from aeromagnetic and gravity highs. It is also suggested from reflection data in the region that a subhorizontal thrust fault underlies the Charleston area at a depth of about 10 km.

Regional Setting

The Charleston area lies within continental crust about 200 km west of the rifted Atlantic margin and 3000 km from the active plate boundary at the mid-Atlantic ridge. It lies on trend with a major oceanic transform fault, the Blake Spur fracture zone. The initial phase of Atlantic rifting in the early

Mesozoic formed numerous, generally northeast-trending graben, bounded by normal faults, that extend along the eastern seaboard between the Appalachian highland and the continental margin. Deformation of the continental margin since successful rifting about 190 m.y. ago consists largely of downward bending toward the Atlantic as the rifted margin cooled and the formation of broad arches and embayments along the margin. These have influenced Coastal Plain sedimentation and warped Quaternary shorelines.

In a few places the Coastal Plain section has been demonstrated to be offset by northeast-trending reverse faults. These offset the Cretaceous-basement contact as much as 100 m or so, show progressive offset through time at rates of 1 m/m.y. or less, and locally offset strata at least as young as Pliocene.

Seismic reflection studies indicate that major sole thrusts, or decollement faults, underlie the crystalline Appalachians at a depth of about 5 km and may extend eastward to depths of about 10 km beneath the Coastal Plain. These faults formed originally during Paleozoic continental collision and involved large horizontal transport. More recently the Appalachian highland must have been rising to maintain its topographic identity, probably with faulting or folding localized along the boundary with the low-lying Piedmont to the east.

General Conclusions

Although much has been learned about earthquakes, structure, and tectonics along the eastern seaboard, the specific source and cause of the 1886 earthquake at Charleston has not yet been identified. Seismicity persists in the upper crust in the meizoseismal area, either because of some long term tectonic characteristic or because of continuing response to the 1886 perturbation.

No large faults have formed since Atlantic rifting in the Charleston area, or apparently elsewhere along the eastern seaboard, with the possible exception of the Appalachian front. The view is now broadly accepted that ongoing deformation and associated earthquakes in the east occurs principally along preexisting structural discontinuities that happen to be favorably oriented in today's stress field. Rates of deformation and frequency of large earthquakes must be quite low.

Little basis has emerged to identify the Charleston area as tectonically or structurally distinct from the rest of the eastern seaboard. To the contrary, most of the geologic features found in the Charleston area are characteristic of the continental margin as a whole. The principal exception is the flood-basalt field, but no causal association with the 1886 earthquake is evident. Enough information is now in hand that various hypotheses to account for the 1886 earthquake have been proposed, several of which are noted below. None provide a basis for restricting large earthquakes to the Charleston area.

Reverse Faults

The presence of Cenozoic reverse faults and earthquakes representing compression across the continental margin have stimulated proposal that sporadic movement of such reverse faults scattered throughout the eastern seaboard is responsible for much of the seismicity in the region, including the 1886 Charleston earthquake. Rates of fault offset and reasonable source dimensions lead to a frequency of magnitude 7 earthquakes along the eastern seaboard of the United States of about 1/1000 years, a rate equivalent to that estimated from seismicity. Although such reverse faulting has been found in the 1886 meizoseismal area, the northeast-trending compression axis suggested by present analysis of modern earthquakes there is not compatible with the reverse-fault mechanism.

Appalachian Decollement

Subhorizontal focal planes in many of the focal mechanism solutions near Charleston, the apparent wide distribution of 1886 aftershocks in South Carolina, and the 1886 intensity pattern have led to suggestion that movement on the Appalachian decollement is involved in generation of the earthquakes near Charleston, and by implication elswhere as well. This movement might produce earthquakes directly or involve aseismic loading of the upper plate to produce earthquakes there. The reverse faults could represent such secondary deformation. Backsliding of the upper plate toward the Atlantic is the preferred mechanism, with up-dip extension possibly at the front of the Appalachian highland.

Earthquake-Defined Fault

The most recent analysis of results from the South Carolina seismic network leads to the suggestion of a north-northeast-trending strike-slip fault as the 1886 source. Earthquakes below 8 km in the meizoseismal area define that map trend and yield a compatible focal-mechanism solution. The northeast-trending compression direction would probably require a late Cenozoic shift in compression direction from that responsible for the reverse faulting in the region. The size of the area so affected is unknown. This hypothesis in no way restricts large earthquakes to the Charleston area, as northeast-trending structure is common throughout the eastern seaboard.

Major Transforms

The location of Charleston seismicity opposite the end of a major oceanic transform fault and some similar relations elsewhere in the world suggest that old crustal features, which controlled location of the major offsets in the trend of original continental rifting, now localize seimicity within the continental margin. The localizing mechanism and style of deformation producing the earthquakes at Charleston are not specified. Other major transforms along the continental margin occur off central Virginia, the Ramapo area, and farther northeast, and lesser ones occur throughout at a spacing of 50-100 km.

Mafic Plugs

The fact that holes in a stressed plate concentrate stress and a crude association in the east of seismicity with some mafic intrusions inferred from aeromagnetics has led to the suggestion that such plugs may localize earthquakes. Chemical alteration of the mafic rocks may make them weaker than the country rock and thus act as holes. Realistic elastic properties do not seem to produce stress differentials sufficient to produce faulting, however, and the long-term kinematics of the model have not been addressed. Although not ubiquitous, mafic plugs are inferred to occur in various parts of the eastern seaboard.

LARGE EARTHQUAKES MAY OCCUR ELSEWHERE

The similarity of Charleston structure to that of the whole eastern seaboard and the fact that no credible tectonic hypothesis restricts large earthquakes to the Charleston area has now shifted the burden of proof. Future large earthquakes are certainly possible in the Charleston area, but, in addition, large earthquakes may also be possible elsewhere along the eastern seaboard.

Eastern neotectonics are still poorly understood, but the work of the past few years provides a solid base of facts and possibilities from which further research can proceed effectively. For regulatory and scientific purposes, existing hypotheses must be tested, uncertainties in existing analysis resolved, promising bodies of data exploited, and well-focussed inquiry pursued further. As before, the directions and rate of progress will depend largely on funding.

In the absence of clear understanding of earthquake tectonics in the east, consideration of Charleston-sized earthquakes elsewhere in the region should also involve estimation of their probability of occurrence. General dispersal of a possible large earthquake over the whole eastern seaboard leads to very low local probabilities. The questions then arise whether some parts of that area are stronger candidates than others for large earthquakes in the foreseeable future, what evidence may bear on the issue, and how probabilities may be affected.

RENOVATION IS A REVOLUTION

by

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INTRODUCTION

One of the most unique changes in the Americans' sense of values has occurred within the last two score years and its vigor is increasing daily throughout the land. In every city one finds a growing number of old houses and commercial and public buildings undergoing renovation. Builders range from individuals to sizable well-financed corporations. Even governments at all levels are playing a role in the renovation of existing buildings.

One of the most compelling reasons for wide-spread renovation is economics. Aside from high interest rates, a family can be housed in renovated structures for a fraction of the cost required for new housing. If one applies the prognostications of economists and real estate investors, it is very easy to reach the conclusion that the economic advantages of rehabilitation will increase with each passing year. In Europe, the practice of rehabilitation is so well established, in fact so deep in their history, that the concept of rehabilitation is so basic that one first thinks of reusing a structure rather than wrecking and building another.

From the view of society, renovation is like "drinking at the fountain of youth." Who has not driven through the slums of New York, Washington, Chicago, Memphis and not asked, "How can a city afford such conditions?" Aside from the social blight, slums are a robber of tax revenues. For every dollar they bring to the city they cost from two to ten. Society can renew itself, at least in some degree, by renovating its aging properties. In addition to the economic imputus to renovate, there is the growing interest in preserving our heritage - of saying to our children through words and deeds that we, as a Nation have something worth preserving. Every year millions visit Williamsburg, Charleston, New Orleans, and San Antonio to visit buildings that stand as symbols of American history, as symbols of some things that reach across the quiet ocean of time and in so doing they invite us to leave behind a lasting legacy. The call is ages old although we in America have only begun to hear it. This call joins hands with economics and demands that the builders find ways to play their role in preserving both the spirit and the utility of that which is bequeathed to us.

OUR CHOICES

Those of us who have chosen to be the builders of buildings have the responsibility to prepare ourselves; both in knowledge and spirit, to play our role in the voyage of our society. As of today we do not have the knowledge and skill to renovate as efficiently and effectively as to build anew. We have not been trained and we have not had the experience, but we do have the ability to learn and to acquire those skills and to do well the new tasks. As architects, engineers and builders we must harness our courage and creativity to the problems of renovation as fast as we and prior generations have been harnessed to the building of skyscrapers and gigantic dams and breath-taking bridges.

MEANS TO PRESERVE

The miracles wrought in the fields of technology have placed in our hands knowledge of materials, methods of analysis and construction, as well as new materials, that make it possible to renovate to a higher level of building quality than was the original construction. The technical challenges are immense because renovation with all of its constraints and complexities does not excuse the making of a mistake simply because the original builder made it.

Our superior knowledge should be applied in the selection and use of materials when renovating. For example, if a slate roof was secured with nails that quickly corrode and fail only a dolt would repeat the error in the name of restoration. If a structural system were found by current knowledge to be extraordinarily vulnerable to service conditions there is no valid argument for not reinforcing it during restoration.

Given these responsibilities, it follows that some changes in structures must be accepted, even expected, as renovation progresses. If this is done with sympathy for and understanding of the original structure the changes may, in intellectual honesty, be regarded not as desecrations but as contributions to the works handed to us by our forebearers.

There are problems whose solution will demand extensive research and the seismic reinforcing of masonry structures is probably the most crying case in point. The amount of floor space and dollar investment associated with ordinary masonry structures is enormous. One look at the photographs of damage following every major earthquake shows us how woefully weak this type of structure is. These structures also have a way of becoming the most densely populated in our entire spectrum of buildings. Research is desperately needed to find means whereby these structures can be economically made safe to inhabit. One can be confident that structural reinforcements will require architectural and spacial changes. But the concept of renovation is certainly compatible with such prioritizing and serving of society, both economically and socially.

Those enthusiasts of Victorian architecture must realize that high parapets, towers, and heavy cornices are extreme risk elements during earthquakes and high winds. It is not impossible to stabilize these symbols of grandeur, but it is extremely expensive. At the risk of being stoned at the door it must be said that their removal or reduction in size should be seriously considered at every opportunity. But if it is any consolation their changes should be regarded as evolutionary adaptations for survival rather than unsympathetic desecrations.

IMPLICATIONS

The implications of well-done renovation as an on-going "way-of-life" are far reaching and profound. It will establish a new base for defining quality housing, alter our attitude toward maintenance, create new trade specialties geared to maintenance, change the amortization and finance periods for construction, stabilize the tax base for our cities, reduce the urban sprawl that wrecks the utilities and transportation services.

Possibly of greater importance are the changes to be expected in the human mind as we become able to look upon our houses and buildings and cities as something to be preserved and passed on rather than something to be used-up and left behind as trash.

So one may say with certainty that "renovation is a revolution".

EARTHQUAKE RESISTANT DESIGN CONSIDERATIONS FOR SOUTHEASTERN UNITED STATES

by

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INTRODUCTION

The intent of this paper is to review present seismic design provisions and to discuss their possible application to Southeastern United States. The paper is written from the perspective of a practicing structural and earthqauke engineer involved in analysis and design of buildings (both new and existing) and development of seismic design requirements for buildings, structures, and highway bridges. The development of earthquake design considerations for Southeastern United States should consider both proposed construction and existing facilities including historical buildings and structures. The potential impact can be both technological and societal. But first a basic question must be posed; does the public consider the risk of loss of life or property from potential earthquake motions great enough to warrant expenditure of the necessary resources to reduce the risk? The following discussion assumes an affirmative response. Pertinent seismic design considerations are discussed for buildings and structures, requirements of current codes and the ATC-3 tentative provisions are reviewed, and suggestions for possible improvements are offered. Some observations on the viability of retrofitting buildings and improving seismic resistance of single family residences are presented. Lastly, suggestions for future research are posed.

SEISMIC DESIGN CONSIDERATIONS

Conclusions based on post earthquake observations of and research into structure response have been incorporated partly into code seismic design provisions. Much of the development has been done by the Structural Engineers Association of California (SEAOC). Until the 1971 San Fernando, California, earthquake the principal seismic design requirements were those in the SEAOC, Recommended Lateral Force Requirements and Commentary, initially published in 1959-60. The Uniform Building Code (UBC) adopted the SEAOC recommendations almost verbatim. Since 1971, seismic design codes and/or regulations in the United States have proliferated - in large part because federal government agencies decided to enter what had been primarily a local or regional matter.

In addition to SEAOC and UBC, there are a number of codes and/or regulations requiring consideration of seismic resistant design including:

American National Standards Institute (ANSI)
Building Officials Conference of America (BOCA)
Southern Building Code (SBC)
Veterans Administration (VA)
General Services Administration (GSA)
Nuclear Regulatory Commission (NRC)
American Association of State Highway and Transportation Officials (AASHTO)

The Applied Technology Council (ATC), under contract with the National Bureau of Standards (NBS) with funding by the National Science Foundation (NSF) and NBS, developed "Tentative Provisions for Development of Seismic Regulations for Buildings" (ATC-3-06) published in June 1978. The NRC and AASHTO requirements will not be discussed because NRC applies to nuclear power plants and AASHTO to bridges.

The seismic design requirements contained in each of the above except the ATC-3-06 follow the general approach of:

1) Determine area seismicity (Z) from a seismic zoning map,

2) Calculate seismic force coefficient (C) considering the fundamental period of vibration (T) of the building,

3) Determine design forces on building based on Z and C, importance or use of building (I), type of structural framing (K), and weight (or

active mass) of building (W). In some codes a site soil factor (S) is also considered.

4) Design the lateral force resisting system considering gravity and seismic or wind loadings,

5) Detail design of structural members and connections. Some codes also require seismic design of nonstructural components and systems such as exterior cladding, partitions, ceilings, heating-ventilating-air conditioning systems, ceilings and light fixtures, and elevators.

Implicit in this approach, except for the ATC provisions, is the concept that the lateral resisting strength of a structure must be increased in proportion to the increase in seismicity or seismic zoning of the area. The levels of seismic forces in current codes implicitly or explicitly consider the damping and energy absorbing or dissipative effects of nonstructural elements. However, this approach has caused misunderstandings that can result in building designs with serious deficiencies, such as inadequate connections or tying together of building components, and inadequate provisions for the occurrence of building deformations in excess of those calculated for the design forces.

The ATC-3-06 provisions are based on the concept, that up to a point, design for increase in seismic force increases the seismic resistance of a building or structure. Beyond that point, buildings whose continuing functioning would be essential in case of a major earthquake have more restrictive design details and connection requirements. The ATC provisions also present a more complete approach to determining the design forces. Maps indicating areas based on acceleration or velocity related coefficients are provided. The ground motions represented are more realistic than in present codes. The type of analyses to be used and the required design details are determined by considering the map area and use of the building. Strength requirements and detail design requirements are given for the four primary structural materials; wood, steel, concrete and masonry. The provisions are structured so they can be adopted by local jurisdictions throughout the United States. Because the ATC provisions are structured so they can be adapted to local jurisdictions, the concept and procedures persented therein would appear to be appropriate for Southeastern United States. However, before they are adopted they should be tried out by making comparative designes of buildings typical for the area. The Building Seismic Safety Council is planning to have trial test designs made for a few buildings in the Charleston area later this year.

SUGGESTIONS FOR IMPROVEMENTS

The observed inadequate behavior (damage) of buildings during earthquakes can be generally classified as due to several causes:

1) Insufficient seismic design force level,
2) inadequate or improper design procedures,
3) inadequate detailing including tying together of building components,
4) inadequate construction quality control, and
5) poor building geometry or configuration.

Based on personal post earthquake observations and review of post earthquake reports, possibly the last three are predominant. Of these three, some tying together and detailing requirements have been included in current codes, although there is still room for improvement. Quality control of contruction is required for some structures in highly seismic areas, but not in most other areas. Considerable effort has been expended by the author and numerous others in trying to develop code-type provisions for building geometry and configuration. Hopefully, within the next few years provisions will be developed.

Another area requiring improvement is the concept of damage being directly correlatable to ground acceleration, or acceleration-related coefficients such as the C value. These are convenient to use in design, but the correlation of observed building damage to recorded peak ground accelerations is poor. The effects of various parameters such as duration of strong ground motion, inherent damping of the type of construction and construction materials, effects of nonstructural components, and ground velocity must be considered (Ref. 1).

RETROFIT OF BUILDINGS

The inventory of buildings and structures that have not been designed for earthquake resistance, but are located in areas subject to potentially damaging earthquakes, far outnumbers those that have been adequately designed. The replacement of such buildings with new adequately designed buildings is not feasible economically. Therefore, this leaves two options:

1) ignore the situation and repair or replace the buildings when and if they are damaged, or

2) evaluate their existing condition and construct appropriate strengthening measures.

The first option will not be discussed herein, but the viablity of option 2 and some of the problems to be encountered will be reviewed. The first question to be answered is one of the acceptance criteria to be used. Should or can existing buildings be brought up to existing codes? Based on the author's experience with evaluation of existing facilities and development of strengthening measures, the answer would be no, not completely.

There are several reasons for this position. Economically, it generally would not be feasible. Possibly for buildings of critical function, historical or other importance, government might provide the required funds However, even then it might not be possible to meet all requirements of the code unless the building is nearly demolished and then rebuilt. For example, replacement of inadequate reinforcing steel in concrete beam to column connections would be impossible. Old buildings may not meet current materials strength requirements. Therefore, an approach based on consideration of the seismic exposure, potential damage, risk to life and safety, use of the building, its age (or code under which it was built) and time to conform seems appropriate. The approach proposed in ATC-3-06 contains some of these considerations. The result is to try to strengthen the building to meet some fraction of current code requirements.

The actual strengthening measures will be affected significantly by the allowable strength or stresses for existing materials. Aesthetics is often important. The disruption impact of construction activities and the economic impact must be considered. The economic burden on the building owner or the tenants may be intolerable. For example, strengthening might require shutdown of operations. For a retail store, the cost of shutdown or moving to another location might put the operation out of business. On the other hand, the owner probably could not raise rents sufficiently to pay for the improvements. These are difficult questions to answer.

From a technical standpoint, it generally is possible to design strengthening measures for the structural and nonstructural elements. However, they often will not or cannot meet all of the code requirements; the seismic resistance can be improved and the potential for damage reduced.

SINGLE FAMILY RESIDENCES

The resistance of single family residences to earthquake motions is dependent on several factors:

1) connection of structure to foundation,

2) stability of cripple or supporting walls when subjected tolateral motions,

3) stiffness and strength of wall coverings such as plaster, gypsum board, particle board, cement stucco or plywood,

4) connection of wall finishes to framing, i.e., anchorage of masonry or other veneer,

5) configuration including abrupt changes in stiffness or strength, and

6) restraint and/or construction of chimneys.

Damage to residences in the May 2, 1983 Coalinga, California, earthquake ($M=6.5$) included numerous examples of each of the above. The 1971 San Fernando earthquake ($M=6.5$), 1969 Santa Rosa ($M=5.2\pm$) and other earthquakes have demonstrated these weaknesses. The improvement of some of these weaknesses can be accomplished quite readily, providing the required funds are available. Anchorage of the structure to the foundations and bracing of the cripple or support walls and partitions (generally only a few, if any need to be strengthened) and connections to the roof or upper stories can be constructed. Improving veneer anchorage is more difficult because often some or all of the veneer will have to be removed and reinstalled if the anchorage is hidden from view. Changing the building configuration is also more difficult unless installation of strengthening braces or walls is feasible. Steel straps can be constructed around chimneys and anchored to the building frame. On occasions where the quality of the masonry is poor, anchorage alone may not be sufficient. In such cases, demolition and reconstruction of the chimney may be the best answer.

FUTURE RESEARCH

There are many cases where research could be beneficial. These include:

1) Improvement in methods of estimating (or calculating) the fundamental building period. As an example, the current approximate formula given in many codes for other than frame structures is $T = 0.05H/(D)^{\frac{1}{2}}$

   where

   D is the length of the building in the direction under consideration and H is its height. However, the resulting T may vary widely from the actual period.

2) Improvement in modelling techniques. Currently, we have very advanced and precise analytical computer programs, but our knowledge of materials response and stiffnesses is lacking. The understanding by practicing engineers of modelling procedures is often nonexistent.

3) Development of code provisions for limiting configurations and geometry, and better connection details.

4) Development of improved design parameters, etc., consideration of duration of motion, effects of velocity, damping, and effects of nonstructural components.

5) Development of better techniques for determining effective ground motions versus recorded motions. Engineers, in a limited way, have developed effective peak ground accelerations, but correlation between effective peak acceleration and structural response (damage) is still very poor.

6) Better interaction between the numerous disciplines involved; planners, geologists, seismologists, geophysicists, risk analysts, structural engineers, architects, building code officials, and code promulgating agencies.

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SEISMIC RETROFIT

by

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THE PROBLEM - THE QUESTION

The question was posed, "Is retrofitting of existing buildings a viable option?" I understand the problem as follows: Is it economically possible to protect life and property from earthquakes by retrofitting existing buildings? Must buildings be demolished and reconstructed to modern earthquake resistant provisions to assure life and property safety? Or do we let occupants of our older, built environment remain "at risk" until the building deteriorates and the owner or developer sees an economic incentive, outside of seismic hazards, to replace the structure? The technology of building rehabilitation together with social and political concerns greatly influence the answers to these questions. The National Science Foundation (NSF) over the past few years has begun to fund research to study the technological and social issues connected with building rehabilitation and seismic retrofit.

RETROFIT - ACCOMPLISHMENTS IN RESEARCH AND PRACTICE

Research

The amount of research on repair and strengthening of buildings for seismic resistance has increased significantly in the past few years. The engineering community and NSF became aware of the need to better understand the technologies of structure retrofit and of how repair or strengthening processes actually affected a building's seismic response about 1970. Reinforced concrete and unreinforced masonry structures were the focus of most retrofit research because buildings constructed of those materials generally suffered the worst damage in earthquakes. Experimental research concentrated on building one-third to full-scale models of structural components, loading and failing those models, repairing and/or strengthening them, and retesting. The models were built with new materials but were designed to older, non-earthquake resistant provisions. Comparison of the retest with original response demonstrated the quality and response of the repair/strengthening material and how the retrofit altered the overall response of the structure. Most experiments used static, reversed cycle loading, but a few by Clough, Mayes and Gulkan at the University of California and by Agbabian, Barnes and Kariotis in southern California were either shake-table or real-time dynamic experiments. The overall results of the retrofit tests provide an excellent, though limited, view of retrofit technology and of the response of the repaired/strengthened structure. Most important, the tests have proven that structures may be repaired and strengthened simply and economically to provide greatly improved ductility, strength and earthquake resistance.

Analytical research oriented toward retrofit has been considerably more limited than experimental research. Analysis of reinforced concrete under cracking and yielding deformations and of rocking masonry units is an extremely difficult task. Research on such analysis is ongoing.

Research on retrofit of whole structures has been extremely limited. The Japanese tested a full size seven-story reinforced concrete shear wallframe building structure and retested the repaired structure.

The author knows of no research on the seismic retrofit of "non structural" building elements like exterior cladding or partition walls.
Further lacking in analytical and experimental investigations is the study of steel, concrete and masonry materials as they actually occur in existing buildings. The deteriorated condition of masonry built in 1840 is much different than masonry constructed in a laboratory in 1980. The behavior of twisted Ransome bars differs from that of new deformed bars in laboratory models of reinforced concrete. And the moment-rotation character of riveted iron frames is not that of welded steel assemblages. Research both in the United States and abroad has lacked understanding of old building materials and of "historic" construction techniques.

Practice

The practice of seismic retrofit and building rehabilitation is far in advance of research. In the United States and particularly in California, architects, engineers and builders have learned the art and craft of retrofit through experience. The 1933 Field Act in California required that all primary and secondary schools built prior to the Act be made as seismically safe as current building code requirements. Over the past 50 years hundreds of California schools have been strengthened for seismic resistance. The collapse of a Veterans Administration Hospital resulting from the 1971 San Fernando Earthquake led to a comprehensive evaluation by the VA of its existing hospital facilities nationwide. VA hospitals in Charleston, South Carolina and in Augusta, Georgia, have been seismically retrofit. Boston has enacted special retrofit provisions for historic buildings. San Francisco enacted a strict parapet ordinance. And the City of Los Angeles recently has required that unreinforced masonry buildings built prior to 1934 be seismically upgraded.

The California Office of the State Architect has helped develop their Title 21 and Title 24 building code provisions oriented toward existing structures and their retrofit. California engineers have learned how to evaluate older reinforced concrete and masonry school structures, to conceive of strengthening procedures and to accomplish both architectural and structural retrofit. The state engineers consistently have taken a very conservative approach in evaluating the strength of the existing building; much of the retrofit has resembled building a new lateral load resistant system within the older gravity load resistant building. Yet some conditions like anchorage capacities, bond of shotcrete-to-brick and attachments for terra-cotta facades had to be estimated or crudely tested on site. Systematic research results were not available. Codes were developed based on experience. With codes in place, research seemed unnecessary.

The Veterans Administration retrofit approach was much the same as for California Schools: match current building codes plus make the facility able to function after an earthquake. Engineers designed new buildings within the old; they used their best judgements to create seismic safety but followed the building code as closely as possible.

San Francisco engineers, with considerable debate, have agreed to securely attach parapets and to structurally connect roof diaphrams to load bearing walls. The parapet ordinance in San Francisco was originally conceived to prevent all facia from falling on occupants running from a building and on sidewalk pedestrians. Furthermore, California engineers have been forced to bring existing buildings up to current seismically resistant standards when a structure has been substantially rehabilitated. Rehabilitation of buildings like the State Capitol, Stanford University Quad, the Cannery and many older San Francisco merchantile establishments have forced them to conceive of retrofit schemes.

The City of Los Angeles foresaw substantial risk of collapse of older unreinforced masonry buildings and enacted Division 68 of their building code which establishes criteria for seismic retrofit. These criteria are substantially different and generally less stringent than having a building meet new building code requirements. Much of the technical rationale behind Division 68 was the observed behavior of unreinforced masonry buildings during the 1971 San Francisco Earthquake and the results of NSF sponsored research by Agbabian, Barnes and Kariotis.

The requirement for retrofit in California has given those engineers a learning-by-doing knowledge of seismic repair/strengthening. Yet the actual adequacy or over-capacity of many of their solutions is yet to be determined. And the retrofit techniques which have been applied to school buildings and hospitals are very expensive, up to 50% to 80% the cost of a new building.

TECHNICAL AND SOCIAL ISSUES

The basic technical issue concerning seismic retrofit is that rehabilitation of an existing structure is a completely different design and construction process than the conceptualization and building of a new structure. The idea that a retrofit for an existing building meet building code provisions for new structures is fallacious because that idea assumes that an existing structure can be evaluated by code provisions. Codes work well on the conceptdesign provisions-construction path, but they cannot work in reverse. The attempt to bring an existing building "up-to-code" results in the California school building technique of constructing a new building within the old.

Economic retrofit depends on the architect's and engineer's art--their judgement of how a system will respond; and it depends on a constructor's craft of matching new structural elements to those existing. Most building codes by their nature as minimum standards, cannot utilize such dependence on art and craft except by such statements as, in the Uniform Building Code, "The provisions of this code are not intended to prevent the use of any material or method of construction... that they are at least the equivalent of that prescribed in this code in suitability, strength,effectiveness, fire resistance, durability, safety and sanitation." New code-like provisions such as Division 68 and Chapters 13 and 14 of ATC-3-06 attempt to utilize an engineer's creative capabilities.

Engineers are reluctant to follow a broad provision like that given above. Without a specific code, an engineer faces liability problems he has avoided by following The Code. An earthquake may prove his art and creative concept lacking; is he then liable for life and property loss?

Economics and the people's desire to preserve historic buildings will force the continued use of existing, currently unsafe structures. The California school building and VA method of retrofit is economically unfeasible for most structures in regions of moderate or even severe seismicity.

The social and political issue becomes do we, the people, want some earthquake safety in our existing structures, or none. Some safety means application of low cost, innovative techniques which may not appear to satisfy new building code criteria.

ACTIONS

Research

Research can do much to clarify and help solve the technical and social issues--the problems. Specific research areas are the following:

1) The current design and construction practice of seismic retrofit must be thoroughly investigated to help establish the art and craft of retrofit.

2) Old metal, reinforced concrete and masonry construction techniques must be evaluated so that modern engineers can better evaluate existing structures.

3) Improved methods of quantifying the quality of existing materials must be developed.

4) Experimental research must be undertaken to examine the response of complete structures and structural and nonstructural elements built using old materials and historic construction techniques.

5) Simple analytical methods to approximate the response of existing buildings must be developed.

6) Code and legal concerns must be examined to determine how retrofit provisions can be applied.

Public policy needs to be developed to demonstrate that earthquake damage is not an "Act of God". The earthquake is the Act; the damage of man-made facilities is preventable.

Retrofit may be economically accomplished in the Southeast as a building is being rehabilitated if architects and engineers are encouraged to artfully construct seismic resistance. The social desire to maintain our historic structures will be achieved as we learn how existing buildings actually behave and how they may be strengthened as opposed to how to meet new building code requirements. A public policy of neglect, let the people remain "at risk" until we build anew, need not be tolerated if thoughtful research and education enlightens designers to economical seismic retrofit procedures.

Finally, in the Southeast the question of earthquake hazard mitigation for existing structures cannot be addressed as a separate technical, social or political issue as it may be in regions of high seismicity like California. Seismic retrofit may reasonably be accomplished as part of a multihazard, strong wind plus earthquake, mitigation scheme. And the mitigation construction will occur during an architectural modernization and rehabilitation of the building.

A PRELIMINARY VIEW OF THE PERCEPTION OF SEISMIC RISK IN THE SOUTHEASTERN UNITED STATES

by

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INTRODUCTION

The U.S. Geological Survey has placed two areas in the southeast into seismic risk zone three (major destructive earthquakes may occur). In contrast with other parts of the country such as California, very little attention has been paid to earthquake risk in the Southeast. This work explores risk assessment of earthquake hazards in the Southeast including both risk estimation (i.e., seismic risk) and risk evaluation (i.e., perception of risk). The seismic risk of earthquakes in five selected urban sites in different seismic areas of the Southeast will be estimated. Then the perception of earthquake risk will be assessed with a survey instrument, administered to samples of professionals, decisionmakers, and the public from each of five sites. Seismic risk is hypothesized to be greater than perceived risk in the Southeast. The survey results will be analyzed for implications relating to the mitigation of hazards to buildings through political and economic institutions. This will serve as a first step for a broader institutional assessment of response to earthquake hazard in the southeast and provide a base for more specific policy recommendations.

DESIGN

Analytical Framework

An analytical framework for the risk assessment comes from Otway and Pahner's (1976) general structure for a risk assessment consisting of two major parts: risk estimation and risk evaluation (see Fig. 1). Risk estimation includes identification and quantification of the physical risk from earthquakes. This paper will only attempt to derive estimates of the seismic risk (probability of an event, E_j) from historic earthquake records and microearthquake data collected in the past two decades. A complete estimation of rick (R_{ij}) would include the consequences (C_{ij}) associated with each event (E_j), requiring data on the building stock throughout the study area and its suceptability to earthquake events. This will be left for later work.

The risk evaluation concerns itself with the perception of risk by the population at risk. To explore the perception of earthquake risk, a survey instrument has been developed for the general public and two key subgroups: the political decisionmakers who would decide upon risk reduction policy such as elected and appointed officials of various government levels and regional planning and zoning board members and the technically trained professionals who would implement any risk reduction policy--planners, architects, and structural engineers. The survey instrument relates the individual's judgement of seismic hazards in his or her area to the standard scale for rating perceived earthquake intensity, the Modified Mercali Intensity scale. The results of the risk estimation and risk evaluation will be compared to determine differences between physical risk and perceived risk.

Selection of Study Sites

Five southeastern sites were chosen for intensive study. These sites are all urban areas of varying populations and characteristics. Each is in a different institutional environment since all are in different states and represents a different set of seismic conditions.

Memphis, Tennessee is the closest major urban area to the New Madrid fault where the major earthquakes of 1811-1812 occurred. These earthquakes were estimated to have had intensities of XI-XII on the Modified Mercali Scale. Earthquakes in this region have the potential to damage dams in the TVA system.

Charleston, South Carolina is the site of the well-known 1886 earthquake that was estimated to have had a modified Mercali intensity of X. Much historic preservation activity is taking place in Charleston and, with the formation of the South Carolina Seismic Consortium, there is a local consciousness of the earthquake hazard.

Atlanta, Georgia is in the Piedmont seismic zone, between the New Madrid and Charleston sites. It is a major metropolitan area with a number of tall buildings. Some of the more recently constructed buildings, such as the Southern Bell building, have been built according to seismic design specifications. Atlanta is an area that has been traditionally less conscious of earthquake hazards.

Huntsville, Alabama is near the intersection of two belts of seismic activity in northern Alabama. It is a medium sized community.

Asheville, North Carolina is in the Appalachian seismic region. It is a medium sized city.

The sites selected, with their varied seismic characteristics and political jurisdictions, illustrate the complexity of the problem of dealing with earthquake hazards in the southeastern United States. This complexity is physical, with different seismic zones and their physical characteristics. Equally important, it is political with a number of states and their political subentities involved. Unlike California, the institutional problem in the Southeast is truly regional. Because of the geology of the region, major earthquakes can readily cause damage in a number of states adding to the complexity of institutional mechanisms for earthquake hazard mitigation.

<u>Risk Estimation</u>

The seismic risk for the 5 test sites was estimated using an intensity-recurrence relationship of the general form:

$\text{Log}_{10} N_c = a - bI_o$; N_c=cummulative number of earthquakes greater than some lower bound

I_o=epicentral intensity of earthquakes on the Modified Mercali Intensity scale (MMI)

Estimates for the "a" and "b" coefficients were obtained either directly from historic records or indirectly from other work in the seismic literature. These estimates were then used to estimate an expected recurrence rate for earthquakes of various MMI levels. Work is under way to estimate the effects of distant earthquakes at each of these sites.

Seismic risk should also be distinguished from physical risk. Physical risk includes consideration of the building stock of a particular site. Atlanta for example has a unique situation with tall buildings. Charleston has a large number of historic buildings. The dams on the tributaries of the Mississippi pose a special problem in the New Madrid zone (Memphis). This type of information is not included in the following very rough seismic risk estimates.

MMI Region	V	VII	X	XII	Sources (for coefficient estimates
Memphis expected every	2 years	18 years	456 years	possible (worst case)	Nuttli, 1974
Huntsville expected every	20 years	120 years	1000 years (worst case)	----	Steigert, 1982
Charleston expected every	18 years	140 years	1000 years (worst case)	----	Tarr, 1977
Atlanta expected every	40-50 years	400-500 years	----	----	Allison, 1981 data set
Asheville expected every	40-50 years	400-500 years	----	----	Bollinger, 1973 (for regional coefficient)

RISK PERCEPTION

Exploratory Planners' Survey

In order to investigate what broad differences might be expected between the southeast and other regions of the country, an exploratory survey was distributed at the 1983 annual meeting of the American Planning Association (see Appendix 1). A map of the United States, divided into five regions, was provided, and the planners were asked to indicate their home region and rank the earthquake hazard in each of the five regions on a 1 to 7 scale. While the sample was small, a most interesting finding from this survey concerned the planners in the southeast region. They perceived the earthquake hazard in their own region significantly lower than planners from the nation as a whole (10% level, one-tailed "Students' t", $t = 1.46$). Moreover, the entire sample rated the Southeast as having the lowest earthquake hazard. Figure 2 illustrates survey results. Several other qualitative responses also proved useful in the formulation of a more general instrument (see Appendix 2) for assessing risk perception in the 5 study sites in the southeast.

Risk Perception at Five Sites

Perception of seismic hazard at the five southeastern study sites will be investigated with a survey instrument among the three previously defined substrata: general adult population, technically trained professionals, and political decision makers. The survey (whose preliminary version is Appendix II) describes earthquakes of different magnitudes in the perceptual terms of the Modified Mercali Intensity scale and asks participants in the study to estimate the frequency of occurrence of earthquakes of various intensities. The survey will be administered by phone in a short 2-3 minute interview.

The sample of the general adult population in the five sites will be randomly selected from telephone exchanges in the respective areas. Since no master list exists for the other two subsamples, and the total population may be quite small in some of the sites, the sampling strategy will attempt to exhaust the total population by using a "snowball" technique (i.e. interviewees will be asked to name colleagues who might be willing to participate in the study). For statistical purposes, the desired sample size per cell is twenty. (20/cell/site = 20 x 3 x 5 = 300 total.)

CONCLUSION

The exploratory survey confirmed a general belief that seismic risks in the Southeast are perceived to be low and pointed to a particular lack of awareness by planners from the Southeast. This should not be too surprising since technically trained people are not much better than nontechnical people in the accuracy of their risk perceptions (Lowrance, 1982: 116). The larger survey of five sites in the Southeast should answer this question more definitively. The results of the earthquake risk perception survey will be compared to estimates of seismic risk combined with a knowledge of local building stock to determine the physical risk. The differences that may exist between physical risk and perceived risk will be evaluated. These differences will be an important input into the process of developing policy alternatives for mitigating the effects of earthquake hazards in the Southeast.

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EARTHQUAKE PREPAREDNESS: THE DYNAMICS OF LONG TERM POLICY INNOVATION

by

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INTRODUCTION

What is the nature of policy innovation in earthquake preparedness? We know little about this question. We do know that earthquakes are an example of the kind of long term, science and technology intensive problem with which government has the greatest difficulty in coping. Government is geared to the political short term. Those who run government usually know little of science and technology. They sense political risks, but not the risks of major natural and technological hazards. Yet, earthquake risks can present political risks. Especially in those states that are earthquake country. We have been observing decision making by state governments. The issue is not the fact of earthquake risk. That is a given. What is not given is whether any state policies will be formulated to deal with those risks, and, if formulated, whether they will be sustained or implemented. What are the forces that are involved in this area? How do they resolve their differences?

LEVELS OF POLICY INNOVATION

There are three levels (or models) of policy innovation. The first (level 1) is the kind of policy that represents an ad hoc, specific action. An earthquake occurs, a law is passed by the state that affects behavior of local government or the private sector, but no major new institution is established at the state level. An example would be The Field Act, passed in 1933 by the California state legislature as a consequence of the Long Beach earthquake of March 1933. This set certain seismic standards in school building construction. While important, ad hoc policies tend to be piecemeal and narrow, often one-shot affairs.

The second model (level 2) is a policy that establishes an ongoing, standing agency--or that provides policy analysis and recommends earthquake preparedness measures. The agency provides continuity. An example is the California Seismic Safety Commission.

The third model (level 3) involves action programs aimed at influencing change more directly, on an ever wider scale. This is generally an extension of model 2, and an example is the Southern California Earthquake Preparedness Project (SCEPP), organizationally a program of the Seismic Safety Commission (SSC), as well as the Federal Emergency Management Agency (FEMA). Each model involves a greater degree of intervention by government into society and the earthquake status quo, a broader and deeper level of intended change. It is perhaps helpful to classify these three models as ad hoc, institutional, and programmatic policies.

How do such policy innovations occur? What are their dynamics?

THE PROCESS

The process of policy innovation has four major stages. It begins with the stage called agenda setting. There is an awareness of a problem by interests inside or outside state government. This awareness phase can be lengthy. Often, there are only a few individuals who share a particular concern. Often, they need a trigger to move an issue from the backburner of the State's agenda to an item of priority. A process of search for an appropriate response then unfolds. It can merge into a later planning phase.

If all goes well, eventually stage two is reached-adoption. Adoption usually involves the passage of law, allocation of financial resources, and provision of legitimacy to state action in a field.

The third stage is implementation. That which is established by the adopted policy--usually a program within or under an agency of government--is carried out. Sometimes, what is implemented is reoriented along the way, based on evaluation. Implementation can be speeded up or slowed down by funds provided, or opposition generated.

Finally, there is stage four, incorporation. At this point, the policy is fully implemented, accepted, and routinized. It is no longer seen as new, innovative. At this point, the results of a particular innovation effort can give way to a new wave of change, often built upon what is now considered "old."

Progress along these stages is not inevitable. Proposals for action may be screened out from the agenda; rejected, rather than adopted; terminated instead of implemented.

THE ACTORS

Who determines which way the process goes? Or whether it moves at all? There are many types of actors involved in the earthquake policy field. Among those who appear most critical are: elected officials, administrators, private industry, the media, and scientists and engineers (the technical community). One of these actors, or a number together, play the essential role in the process of earthquake entrepreneur. The earthquake entrepreneur is the advocate for policy innovation in earthquake preparedness. He or she or it becomes the moving force for change. Ideally, a mark of success for earthquake policy innovation occurs when "it" is the entrepreneur in the sense that individuals give way to institutions, and advocacy gets an organizational base in government.

The role of the earthquake entrepreneur is exceedingly difficult. In our study of policy innovation in three states, we have focused on this role. We have been tracking developments in these states, California, Nevada, and South Carolina. The states share a common threat--the earthquake. They differ in where they stand in terms of policy innovation.

CALIFORNIA: LEVEL THREE INNOVATION

California saw a number of ad hoc policy innovations prior to the 1970s. Beginning in 1971, it moved to a new level of policy activity. The trigger was the San Fernando earthquake of 1971. That event moved earthquake policy to the fore of state decision making. There had been awareness of the threat and, indeed, there had been some new search by a small group of technical, legislative, and bureaucratic entrepreneurs. But they had been lonely voices. The earthquake, which took 58 lives and imposed $500,000,000 in damages, made it possible for them to gain allies, and build a coalition broad enough to embrace the governor and legislature and result, eventually, in 1974, in the establishment of the Seismic Safety Commission (SSC).

The SSC, in succeeding years, institutionalized entrepreneurship, and became a force in continuous search for ways to improve earthquake preparedness. It was a small, relatively low-profile agency headed by a part-time group of commissioners who were essentially volunteers. It was a policy analysis agency that sought change through influencing other state agencies. In recent years, however, it has become somewhat reluctantly an agency with its own action programs, as it was engulfed in a level three innovation process.

Awareness that more had to be done in earthquake preparedness began with the Palmdale Bulge in the mid-1970s. It was accompanied by a heightened sense of concern that an earthquake prediction would be issued before anyone was ready for such a novel technology. Also, new scientific findings, based on long term recurrence intervals, suggested that a repeat of the 1857 catastrophic quake along the southern San Andreas was due.

The feeling grew that California was running out of time and that SSC was cutting too narrow a swath in earthquake policy. Also, it was felt, particularly in the California legislature, that the state disaster agency, Office of Emergency Services (OES), was organizationally geared to responde to moderate earthquakes. It was not ready to prepare for the problems presented by a catastrophic earthquake, much less a prediction of one.

A sequence of events that moved earthquake policy in California to the fore again. This time, however, it was a matter of federal as well as state impetus. President Jimmy Carter became involved, as did Governor Jerry Brown. The record should show, however, that the most significant actors--the earthquake entrepreneurs--were Charles Thiel in the Federal Emergency Management Agency (FEMA) and Joe Lang of the California legislative staff. They led the way in creating a federal-state coalition that permitted what was eventually called SCEPP to be born. SCEPP--the Southern California Earthquake Preparedness Project--was established as a project under SSC in September 1980. The saga of SCEPP is important in its own right and deserves a full telling. Suffice it to say here, that SCEPP was created with federal and state funds to fill a perceived planning gap in California earthquake policy, and it has been working since its birth in filling that gap.

At the time SCEPP was created as an intergovernmental effort, the State of California, on its own, was also working to fill a gap perceived by the governor and a key aide, William Whitson. SCEPP focused primarily on government and business planning partners, such as the City of Los Angeles, San Bernardino County, and Security Pacific Bank. It worked exclusively in the southern California region. The Governor's Task Force, as the entity that Brown created was called, had as its main purpose citizen action throughout California. SCEPP devoted attention to earthquake prediction, and general preparedness. The Task Force was oriented toward citizen self-help after the quake, in the first 72 hours. Both dealt with the Great Earthquake. In effect, the SSC had been a response to the San Fernando quake. SCEPP and the Task Force were a response to the threat of a coming catastrophic quake or credible prediction thereof.

In 1982, the Task Force was brought under SSC auspices. SSC thus had both programs under its wing. California was actively having forcefully in a level three policy innovation mode.The only problem was that this required continuous political support. However, Mayor Bradley of Los Angeles, an earthquake-oriented individual, did not become Governor Bradley in 1983, as expected. The individual who did become governor, George Deukmejian, was an earthquake policy unknown, and this created great uncertainties for SSC, SCEPP, and the Task Force. Survival, not growth, became the issue. In July 1983, the State of California finally agreed on a budget for the next year. The decision was to terminate (i.e., not fund) further Task Force work, but to contribute $300,000 in state money to keep SCEPP going one more year. With federal FEMA willing to contribute another $450,000, SCEPP will therefore have $750,000. What happens after July 1984, is undetermined. The Coalinga earthquake of May 2, 1983 may or may not have played a role in the state's decision making process concerning the Task Force and SCEPP. It did not help the Task Force, given the governor's determination to cut budgets wherever he could. It may have helped with SCEPP, this being a symbol of at least some California commitment.

While California is perhaps no where near as prepared as it needs to be for earthquakes, especially a great one, it is relatively far along relative to other states. It is constantly being pressed to transfer its experience elsewhere. The problem is that California still has a long way to go in terms of meeting its own threat. It is noteworthy that innovation has been accompanied by consolidation, at least in terms of personnel. Former SCEPP director, Richard Andrews, is now director of SSC, and former director of SSC, Robert Olson, guided the Task Force during its last year.

NEVADA - SLIPPING BACK FROM LEVEL TWO

Nevada is presently slipping back from level two policymaking. It went forward, almost to the point of adoption of a Nevada version of a Seismic Safety Commission. It suffered instead a rejection, and now is moving backward. It is close to the worst of all worlds in earthquake policy innovation--one in which there is an absence of entrepreneurship.

It did not start out this way. On July 1, 1978, Governor Mike O'Callaghan received a note from Robert Olson, then executive director of California's SSC. While aware of the earthquake threat, O'Callaghan had been slow to move, professional associate. Olson noted that California was active in earthquake preparedness,and Utah and Montana, among other states, were also getting active. "We are 'surrounding' you," Olson told O'Callaghan. He asked the governor when Nevada was going to move. This communication was the trigger for getting a policy innovation process started.

O'Callaghan asked his science adviser, Gilbert Cochran, to take the lead, directing him to establish an ad hoc Panel on Seismic Hazard Mitigation. The ad hoc panel included a crosssection of university, business, and governmental representatives. Its mandate was to assess the problem and recommend policy action.

Those who emerged as earthquake entrepreneurs during this period, aside from O'Callaghan and Cochran, were John Bonell, chairman of tne panel, and retired chairman of the Civil Engineering Department of the University of Nevada - Reno. Also important was Merrily Kronberg, a mid-level administrator with geological training, based in the State Civil Defense and Disaster Assistance Agency.

The ad hoc panel forwarded its interim report to O'Callaghan on December 26, 1978. There were various recommendations to deal with an earthquake threat found to be real and growing in the Reno/Carson City area. The panel's top recommendation was to do what California had done, and to establish a Seismic Safety Council with a five year life to try to bring "order out of chaos."

O'Callaghan received the report, but could do nothing more with it than to send copies to the legislature and the man who would shortly take his place as governor in one month, Robert List. O'Callaghan had chosen not to run for another term. The governor who had initiated the surge would not be in a position to see the process through.

The new governor did not adopt the ad hoc panel's report. Instead,he rejected it by simply ignoring what the panel had done. The panel got a hearing in the legislature, but nothing else. In June 1979, the panel published its final report and was terminated.

There had thus been agenda setting, followed by rejection of the proposed action. O'Callaghan was out of the picture. Cochran, went back to his former position at the Desert Research Institute of the University of Nevada. Along with Kronberg and Bonell, he tried to keep the issue from going off the state agenda. He had allies in the Reno Chapter of the Nevada Society of Professional Engineers. This body attempted to take the case to a wider public, publishing a series of newsletters for general distribution. There were presentations involving scientific and technical professionals seeking to explain the dangers to the general public. The media gave modest attention to the activities, which were largely limited to Reno-Carson City. There were some results in the sense that a state legislator representing this area decided to sponsor a second attempt to get a bill adopting a Seismic Safety Council enacted.

This legislator, however, did not control the key committee whose support was essential. The chairman of that committee was not convinced there was a problem, since, as he noted, no one had died from an earthquake in Nevada as far as anyone knew. In 1983, the Reno Chapter of the American Society of Professional Engineers is again promoting a bill to establish a Seismic Safety Council. The prospects are poor at best. Like other states, Nevada has severe financial problems. It is not looking to create a new agency.

Worse, agenda setting is regressing. Nevada is moving backwards, placing earthquake preparedness on the backburner. The original earthquake entrepreneurs have all but gone: first O'Callaghan, then Bonell. Now Cochran and Kronberg are moving on to other pursuits, having fought the good fight. There are limits to entrepreneurship, and efforts have been expended over years.

There is some potential that the baton of leadership will be passed. There are two individuals, both geologists from the Division of Earth Sciences, University of Nevada - Las Vegas, who may bring renewed energy to the cause. They have submitted a proposal to FEMA to do a vulnerability study and produce a natural hazards map for Nevada. If FEMA provides this support, these two individuals may be able to keep some semblance of interest alive, via a level one policy action. It is ironic that policy innovation in Nevada may now depend on decisions from outside the state, since there is so little likelihood of action from inside state government. It is ironic, but this situation is not unique.

SOUTH CAROLINA - INCREMENTAL AGENDA SETTING

South Carolina has not gone up far enough in earthquake preparedness policy to have had the downs now being suffered in Nevada. It is moving forward, incrementally. However, to the extent earthquake preparedness is moving slowly forward on the South Carolina policy agenda, it is doing so, in part, because South Carolina's inside entrepreneurs have what those in California have, and those in Nevada would like to have, namely, federal support.

South Carolina is on the long climb up the hill of policy innovation. Earthquake entrepreneurs are trying to move earthquake preparedness from the backburner to a priority on the state agenda where it might be possible to consider a range of policy innovation.

The principal inside entrepreneurs are Joyce Bagwell and Charles Lindbergh. Bagwell is a member of the Geology Department of the Baptist College of Charleston; Lindbergh is head of the Civil Engineering Department at The Citadel. They are working in parallel, taking somewhat different approaches. Bagwell, seeking to influence government indirectly, is working primarily at public awareness. She gives frequent talks to citizen groups and schools, and utilizes the media to advantage. Lindbergh appears more willing to work directly upon government in seeking to influence officials to adopt earthquake preparedness policies. Recently, for example, Lindbergh testified before Congress.

Of great importance to what is happening in South Carolina is the encouragement of the federal government. Indeed, it may be said that the major trigger to accelerate entrepreneurial activity within South Carolina has been the stimulus the inside entrepreneurs have received from outside. In September 1981, USGS and FEMA cosponsored a conference on Eastern earthquakes. Bagwell and Lindbergh were invited. In April 1982, largely as an outgrowth of discussions initiated at this conference, a South Carolina Consortium on Seismic Safety was established. Composed of scientists, city/state officials, and social scientists, the consortium was envisioned as a prototype for the whole Southeast. Bagwell and Lindbergh were co-chairmen of the Consortium, which was essentially a voluntary association of individuals sharing a common concern. This consortium developed a White Paper containing a threat analysis that was presented at a meeting in May 1982 to representatives from the Southeast.

Also, in May 1982, there was a meeting in St. Louis cosponsored by FEMA and USGS concerned with the New Madrid earthquake problem. Lindbergh went to that meeting and was briefed on studies under way in the central United States. The question came up as to what was being done in the East, particularly the

Charleston area. Lindbergh responded at the meeting with a pre-proposal involving vulnerability analyses to be undertaken by The Citadel. This proposal was later submitted formally through the South Carolina Department of Disaster Preparedness to FEMA. In September 1982, FEMA provided $41,000 for a 15 month project.

On November 15-16, 1982, with federal support, the South Carolina Consortium held a conference at the Baptist College of Charleston. There, the consortium heard from individuals familiar with the earthquake preparedness situation in Utah and California. These individuals sought to convey to South Carolina some of the lessons learned from attempts at preparedness there.

Since that meeting, there have been a number of informal discussions within South Carolina, as well as work under way concerned with the vulnerability study. This study has provided a vehicle around which communication between state and local disaster officials and the technical community has proceeded. The present conference, devoted to "The 1886 Charleston, South Carolina Earthquake and Its Implications for Today," is another event in the sequence of events that has continued the momentum begun in 1981. It can be said that progress is taking place incrementally. The South Carolina entrepreneurs--Lindbergh and Bagwell--are gaining allies. The inside coalition is growing--aided significantly by federal support.

The real problem in South Carolina appears to be the same as in Nevada: state commitment. Earthquakes are on the agenda of state government in terms of awareness, but not high on the agenda in terms of money and action programs. From the perspective of state officials, there continue to be more pressing problems on their agenda than earthquakes. To move from awareness to action more quickly than the increments of today may require a dramatic trigger--perhaps an earthquake itself.

CONCLUSIONS

What factors have contributed to moving forward or holding back earthquake policy innovation in the three states studied?

First, it appears that if there is a genuine threat, there is a likelihood that there will be those who are aware of the threat and who are ready to play the essential entrepreneurial role. Why they are there, in a state of readiness, is a question whose answers are to be found in psychology rather than political science and public administration. It is noteworthy that in Nevada, even as old entrepreneurs phase out, new ones are in the wings. Often, the initial entrepreneurs are technical specialists.

Second, the problem is usually not awareness on the part of state policymakers. It is getting action. Getting action requires convincing such policymakers a problem is serious enough to take precedence over others crying for attention.

Third, the ideal entrepreneur for earthquake policy is abureaucratic entrepreneur--an agency in the system with the single mission of earthquake preparedness. The great virtue of tne bureaucratic entrepreneur is continuity. Given the long term nature of the earthquake threat, there must be steady pressure for preparedness. Hence, a strong agency is the best entrepreneur in a field such as this.

Fourth, the creation of such an agency is itself a resultant of a policy change process. Such an agency is an example of second level innovation. California has gone through such an innovation experience, and is now at the third level of action oriented programs. What it took to get a Seismic Safety Commission established was a serious earthquake. Unfortunately, people had to die, and then the existing entrepreneurs had a trigger for enlarging their coalition to a point sufficient to get adoption.

Fifth, in the absence of an earthquake, getting second order innovation is a difficult task indeed. Nevada came close, owing to the existence of an earthquake entrepreneur at the most strategic state position of all, that of governor. But this individual left office before the decision on adoption could be made, and, with a new governor, the decision went the other way. The state has moved backward since then, a fact pointing up the degree to which policy progress in this field can turn to policy regress.

Sixth, South Carolina is a state at the very front end of agenda setting. It is in the awareness-building phase of agenda setting. That it is there at all illuminates the significance of a vertical coalition between outside federal officials and inside, nongovernmental state entrepreneurs. They are linked in an informal, incremental effort in consciousness raising. The coalition of interest is growing. Thus far, a trigger for action at the state policy level has been lacking.

Seventh, California reveals the opportunities and problems of third level innovation. It has moved beyond institutional innovation of a kind represented by SSC and has gotten into the business of running programs such as SCEPP, and (up to July 1983) the Governor's Task Force. Running action programs is a major undertaking, and this is particularly so in the case of SCEPP, which is at the very frontier of earthquake policy innovation in this country. SSC was and is strictly a state agency. But SCEPP, from the outset, has been a federal-state program. Who owns an intergovernmental program of this kind? When funds are equal and goals compatible, the question may not be that important. But if funds become unequal and goals grow less identical, there can be problems--especially when progress are still in an implementation mode. The lessons of California are many, and still evolving.

Eighth, those who are early in the earthquake policy field, such as South Carolina, have one benefit of being new in this area: they can observe those who are ahead, learn from what they see, adapt the models that make sense, and transfer/utilize them as appropriate. They can move directly to level two, as Nevada tried, and almost did. Or, even to level three, in the manner of California. But in adapting models from other states, they should learn the problems as well as benefits of certain innovation experiences. Most of all, they should note the long term nature of earthquake entrepreneurship. What one person or institution starts, another may have to carry on--unless,of course, the earthquake intervenes.

NOTES

1. This will be done by the writer as part of a report to the National Science Foundation in February 1984. An early report on the initial

stages of SCEPP was published as "Applying Earthquake Prediction to Southern California: Preliminary Notes on an Intergovernmental Project," in Third International Earthquake Microzonation Conference Proceedings, Vol.III (Seattle: University of Washington, 1982), pp. 1513-1526.

2. This account is based, in part, on the work of Ann DeWitt Watts and her monograph, "The Potential for Earthquake Policy in South Carolina: A State in the 'Awareness Stage'" (Syracuse, N.Y.: Syracuse Research Corporation, 1982), as well as subsequent research by the writer.

THE CURRENT STATE OF EARTHQUAKE HAZARD AWARENESS IN THE SOUTHEASTERN UNITED STATES

by

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INTRODUCTION

The current state of earthquake hazard awareness in the Southeastern United States depends upon to whom one is talking and the scope of involvement of a person. Since the 1981 Knoxville National Conference on Earthquakes and Earthquake Engineering in the Eastern United States, and the USGS/FEMA sponsored workshop on Earthquake Preparedness in the Eastern United States, the state of hazard awareness has been elevated. An outgrowth of these meetings has been the establishment of an ad hoc committee with cochairmen elected to implement the plans to increase hazard awareness and preparedness in the Southeastern part of the United States. The first positive step was taken in the spring of 1982 when the South Carolina Seismic Safety Consortium (SCSSC) was established. Two workshop conferences were held during 1982. A white paper was drafted as a working tool to direct the members of the SCSSC. The approximately sixty members who attended the two conferences have become increasingly aware that not only do earthquakes occur in the area, but that preparedness plans to respond to a damaging earthquake do not exist. The degree of awareness of the South Carolina low country could best be understood by knowing the events that have taken place since 1974. After an explanation in the following section of the events that have caused awareness on part of the residents, the author will categorize the current-state-of-earthquake hazard awareness and give the target audience that should be immediately addressed.

This description of earthquake hazard awareness in the Southeastern United States is based upon nine years of personal involvement with monitoring the lower South Carolina seismic mini-network, conducting intensity surveys of felt earthquakes in the Summerville-Charleston area, and presenting earthquake education programs to civic clubs, school groups, and church groups concerning the seismic activity and monitoring equipment at the Baptist College at Charleston.

BACKGROUND OF SEISMIC AWARENESS

After the November 22, 1974, earthquake in the Middleton Gardens area (15 Km Northwest of Charleston, South Carolina, M=3.8), the author became involved with operating portable seismometers to detect aftershocks. In April 1975, another tremor occurred (M=2.5) and the author helped Dr. Pradeep Talwani, University of South Carolina, with intensity surveys. In the summer of 1975, Mr. Ken King (USGS) came to the area to survey and establish a mini-network system around the Middleton Gardens area. From November 1975 until March 1976, noise level surveys were conducted and sites for five stations were selected. At Middleton Place, a four component system was installed. The nine channels were relayed to the Baptist College at Charleston Geology Lab by telephone data lines. On March 22, 1976, the nine-stations network was in operation. In March 1983, the network was expanded to a 31-channel network.

The first local earthquake to be recorded by the network occurred Januarv 18, 1977. It was M=3.0. (Snow, unusual for the area, had begun falling thirty minutes prior to this 1:29 p.m. EST event, making residents well aware of environmental conditions.) Door to door surveys were conducted and an isoseismal map was drawn. The combined efforts of David Amick of University of South Carolina (U.S.C.) and the author received excellent responses from residents in Summerville and North Charleston area. This earthquake was not felt in the downtown Charleston area; however, through the news media the residents became aware of the event.

March 30, 1977, the second instrumentally recorded and felt event occurred in the Summerville area. It was not as large (M=2.5), but the number of reports warranted an intensity survey from which isoseismal maps were drawn. By this time the residents were aware of the monitoring center at the Baptist College mainly through television and newspaper coverages.

December 2, 1977, was a day that brought national attention to the area. Sonic booms were so strong and frequent in a short period of time in the Charleston-Summerville area, the residents thought an earthquake had occurred. In fact, between the period of 8:45 a.m. EST and 9:30 a.m. EST there were several episodes of explosive sounds, rattling of doors and windows to the point of causing concern to the citizens. Later that Friday afternoon the New Jersey coast was experiencing the same type of events. The events in New Jersey and Charleston on the same day drew the attention of the national television network, ABC. The sonic booms had registered on the seismic equipment. Obviously, the signature was quite different from an earthquake. The public was given this information.

December 15, 1977, was unique in that sonic booms and two earthquakes occurred within twelve hours of one another. The residents of the tri-county area either by experience or hearing the news reports were made very much aware momentarily of earthquakes.

The magnitude of the 2:15 a.m. EST earthquake was 2.0, whereas, the magnitude of the 2:16 p.m. EST was 2.5. Intensity surveys were conducted and an isoseismal map was done for the larger event.

Seismically, everything was relatively quiet in 1978 until 6:58 p.m. EST on September 7. The earthquake sounded like a train as it rumbled through the Summerville area. The magnitude of this event was 2.7, and once again, an intensity survey was conducted. The epicenter of the earthquake was instrumentally determined by Susan Rhea (USGS) and David Amick (USC). It was felt in the Summerville-North Charleston area.

In March and August, 1979, there were small tremors, but these were not widely felt. Thus, not enough felt reports were received to warrant isoseismal maps drawn.

In 1980, there were three felt earthquakes in the South Carolina low country. On June 22, 1980, a M=2.1 event occurred in the Lincolnville, South Carolina area. After thirty phone calls to area residents, it was discovered that most residents were not home on that Sunday afternoon or they were unaware of an earthquake having occurred. A Summerville resident called to report that as she was standing on a stepladder to change a light bulb, she heard a noise and felt the ladder tremble. It was later determined she lived one and one-half miles away from the instrumentally determined epicenter. About three hours later, another earthquake of M=1.6 occurred. One would not expect a magnitude of this size to be felt by anyone. Yet, a call from a Lincolnville resident was received asking if there had been a tremor at 7:35 p.m. EST, because something had shaken his house. Upon checking the helicorder records, the seismic event was in evidence.

From the determination of the epicenter by USGS and knowing the location of the reporting resident's home, it was interesting to note that he lived just about at the instrumentally determined epicenter.

The September 1, 1980, earthquake awakened some residents. It was a magnitude of 2.0. The Summerville police department received several calls shortly after 1:45 a.m. EDST asking if a tremor had occurred. The next morning, the monitoring station at Baptist College received calls asking if an earthquake had occurred. An intensity survey was conducted by the personnel and geology students at Baptist College. Reports indicated that beds and/or houses were shaken. There were no reports from the downtown Charleston area. A resident of Kiawah Island reported that he was sleeping in a hammock on his porch and was awakened by a rumbling. Other members of his household were awakened also. He was located 66 Km (41 miles) from the determined epicenter.

The earthquake of March 19, 1981, was M=2.3, occurred at 11:33:55 p.m. EST, and was noted by relatively few individuals. There were scattered reports from Goose Creek, Ladson, and Summerville area residents. Due to the lack of reports, an isoseismal map was not drawn.

Nearly a year went by with no felt seismic activity. Then on Sunday evening, February 28, 1982, at 10:33 p.m. EST, residents of the Summerville area were once again made aware of earthquakes. The explosive sound with little rumbling startled quite a number of persons. The next day intensity suveys were conducted, and an isoseismal map was drawn. This event (M=2.6) occurred nearer the Middleton Gardens area than the previous ones mentioned in this paper. However, it was still not felt in the peninsula area of Charleston. The news media's account probably made some residents of Charleston aware that the event occurred, and it was assuredly on the minds of the residents in and around the Summerville area. These were perhaps the largest number of responses to this event as compared to the others mentioned above. Over three hundred responses to the survey were tabulated. The other intensity surveys ranged from 75 reports to 200 reports.

The most recent seismic event occurred March 22, 1983. It was magnitude 2.0 and from the number of people feeling the tremor, no isoseismal maps were drawn.

The account of the felt events reveals how the residents of a comparatively small area are aware of earthquakes and how the news media coverage exends this awareness to the other South Carolina's low country residents. A staff member responsible for safety policies at the Coastal Rehabilitation Center at Ladson, South Carolina, conducted an earthquake drill at this facility in the Spring of 1982. Her action was prompted by the awareness that resulted from the small earth tremors that had been felt. This was a first for not only this area but in the Southeast--or could it be said in Eastern United States.

CATEGORIES OF EARTHQUAKE HAZARD AWARENESS AND PREPAREDNESS

Based upon the background information of recent seismic activity there appears to be three major groups in which levels of awareness differ, but very little, if any, differences in preparedness exist.

Category I:

1. Attendees to 1981 Knoxville, Tennessee Conference.
2. Members of South Carolina Seismic Safety Consortium.
3. Vulnerability study group for Charleston, South Carolina, area.
4. Disaster preparedness personnel and military personnel responsible for safety.

Level of Awareness: Very high
Level of Preparedness: Beginning

Category II:

1. City and County officials of the Dorchester, Charleston, and Berkeley South Carolina area.
2. Summerville area residents that have experienced recent minor earthquakes/or sonic booms and have responded to intensity surveys.
3. Beach residents that have felt sonic booms.
4. Lifelong residents/or residents in area for past 5 years of Charleston area that are reminded periodically through news media of the anniversary of 1886.
5. Civic groups/school groups that have had programs on the mini-network system at Baptist College.

Level of Awareness: Moderate
Level of Preparedness: None

Category III:

1. New residents in the Charleston-Summerville area.
2. Residents outside of South Carolina's low country areas in central and upper part of South Carolina

Level of Awareness: Zero
Level of Preparedness: None

ACTIONS TO IMPROVE THE STATE OF EARTQUAKE HAZARD AWARENESS IN THE NEXT 5-10 YEARS

The target audience to be addressed first appears to be those of category III (the least aware). However, utilizing the awareness of category I, members could raise the level of awareness within Category II and III. School board members, administrators, teachers, public officials, realtors, insurance agents, neighbors, and members of some civic groups were interviewed about the current state of awareness and asked what was needed. Their responses were the basis for the following action plans.

1. Establish an effective education program.

2. Utilize the existing products on earthquake preparedness that FEMA and others are compiling and modify them to specific needs in the southeastern region.

3. Incorporate volunteer organizations to aid in the teaching earthquake preparedness.

4. Set up workshops to train volunteers, teachers, public officials and other representative groups in earthquake preparedness.

5. Provide knowledge and tools to support groups to promote earthquake safety. (e.g. fire departments, police)

6. Utilize existing earthquake curriculum for schools, and modify and enhance for the southeastern region.

7. Through training sessions develop a plan for earthquake drills for schools, homes, and special audiences.

8. Design an information package for the education of the news media.

9. Establish a local avenue for disseminating books, films, tapes, brochures for the public.

10. Establish a speaker's bureau where trained volunteers are available to speak to groups.

CONCLUSION

The current state of earthquake hazard awareness in lower South Carolina has increased in the last two years, but awareness to the point of action to preparedness is still in the infancy stage. <u>To bring these action plans into focus an earthquake education center should be established in the region.</u> Baptist College is regarded by the public, media, and local emergency managers to be a primary focal point for earthquake information. Baptist College is seeking funds from FEMA to establish an Earthquake Education Center to carry out the actions presented in this paper.

INCREASING HAZARD AWARENESS IN THE SOUTHEAST: BARRIERS AND RECOMMENDATIONS

by

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The extent to which residents in the Southeastern United States were and are aware of the seismic hazard of the region is an empirical question that we have little information to answer. Even though the Charleston, South Carolina, earthquake occurred only 20 years before the well-remembered 1906 San Francisco quake and a good photographic record of the quake's effects exists, it is doubtful that current regional residents, especially those outside the Charleston area, are aware of the regional earthquake threat. We do know, however, that without such awareness, changes in seismic safety practices will not take place.

ASSUMPTIONS

Two assumptions will be made in this discussion. The first assumption is that general seismic hazard awareness is currently low in the Southeast and an increase in awareness is necessary to improve both preparedness (the ability to respond to an earthquake event) and hazard mitigation (the ability to reduce losses prior to an earthquake).

The second assumption is that strategies to improve seismic hazard awareness are not uniform, but must be targeted to particular audiences. There are two general types of audiences to whom efforts to increase hazard awareness should be addressed -- key actors (those elected and appointed officials who are involved in the development and implementation of seismic safety policies) and the general public. While these are two very different audiences, they are each composed of diverse groups and should not be considered uniform for purposes of developing awareness-increasing strategies. Certain strategies and emphases may be more successful with some groups than with others.

Let us consider these two general types of audiences, the type of hazard awareness information that would be important to convey to them, some problems involving that dissemination, and possible strategies for overcoming those problems.

KEY ACTORS

The purpose of increasing hazard awareness among key actors is to promote a climate in which seismic safety issues are not summarily dismissed as inconsequential because the threat of a major damaging earthquake is considered improbable.

Research findings indicate that four major problems affect seismic hazard awareness of key actors:

> Problem 1: Hazard information, especially when couched in the probablistic language of science, may be interpreted to indicate that the threat is negligible.

Often when probabilities are low or recurrence intervals extremely long, decisionmakers may not become sufficiently concerned to give further attention to the threat.

> Problem 2: The transferrence of general scientific information about the hazard to key actors is not sufficient to motivate action.

Even if key actors become aware that a threat exists, they often do not consider further action for a variety of reasons -- they may not be aware of actions that could be taken, or they may have insufficient resources (financial as well as available expert personnel) to implement new seismic safety programs.

> Problem 3: For seismic safety policies to be considered for adoption by particular key actors, the problem of low salience (or importance with respect to other concerns) must be overcome.

Seismic safety must compete with all other issues that confront key actors; and, especially by elected officials, it can easily be given low priority for action among other, more pressing, daily issues in the political arena.

Problem 4: Proposed seismic safety policies may be defeated if they require too much resource investment or if they are not integrated with other, more salient, on-going concerns of the key actor.

To address these problems, the following recommendations are proposed:

Recommendation 1: Geoscientific hazard information should be disseminated in a language and with a focus appropriate to the target audience.

For example, planners and those involved in zoning decisions may find information on liquifaction to be useful if presented using a microzonation approach, while not being particularly interested in the theoretical basis of scientific instrumentation studies.

Recommendation 2: While it is important to present "worst case" scenarios in order to dramatize the potential loss for an area, scenarios for lower magnitude events should also be developed.

Because maximum likely earthquakes have low probabilities and extremely long recurrence intervals, they can more easily be dismissed as unlikely events. But given the construction practices and attenuation characteristics of the Southeast region, lower magnitude events may cause may cause excessive damage. It would be more difficult to dismiss lower magnitude, yet damaging and life threatening, events that have a higher probability of occurring or that are likely to occur more frequently.

Recommendation 3: Vulnerability assessment reports and hazard maps must include not only the types of problems that exist, but a set of options for beginning to address those problems by specific groups of key actors- (planners, emergency service personnel, medical services, building inspectors, elected officials, etc.)

Recommendation 4: Preliminarily, options for addressing problems should not be modelled on California, but should start with achievable goals and reasonable progress based on the Southeast's current level of emergency response capabilities and current structural and zoning policies.

Recommendation 5: Given the potential regional nature of an earthquake disaster in the Southeast, emergency response planning should be conducted at a regional level.

Recommendation 6: In order to overcome feelings that seismic safety policy development presents an overwhelming task, these planning efforts should be integrated with other emergency response concerns (for both natural and technological disasters) and urban and regional development projects.

THE GENERAL PUBLIC

The purpose of raising the seismic hazard awareness level of the general public is to convice them of the need to take protective and preparedness actions for a potentially destructive earthquake. The goals of such programs in areas threatened by regional, destructive quakes are twofold: (1) to reduce the numbers of people injured and killed by the earthquake and (2) to improve public self-sufficiency during the immediate post-impact period.

Five major problems have been identified for educational programs dealing with increasing seismic hazard awareness among the general public:

Problem 1: Especially in areas that have not experienced damaging earthquake events in recent history, highly technical or overly historical programs may not adequately convey the sense of currently living "at risk," which is a major motivation for taking precautionary actions.

Problem 2: Media presentations, even those on television, often reach limited audiences because they must compete with other "entertainment" features.

Problem 3: Even when major efforts are made to reach the public through the media or by the distribution of educational materials, the duration of such educational campaigns is often limited, resulting in the rapid dissipation of impacts.

One-shot or limited efforts with no follow-up may temporarily raise hazard awareness levels but are often insufficient to instill knowledge concerning post-quake actions. This problem is especially likely to occur in areas of low seismicity, like the Southeast, where "folk knowledge" concerning what to do during and after an earthquake is not a part of the regional culture.

Problem 4: No one type of hazard awareness problem is sufficient to reach all segments of the general public.

The general public is not uniform, but is composed of various social groups of different ages with different educational, ethnic, and occupational backgrounds.

Problem 5: Individuals often do not take earthquake preparedness actions on their own because of a belief that the government can handle post-event problems.

This reliance on governmental resources may be particularly troublesome in the Southeast where the potential regional effects of a major quake are highly likely and the current level of governmental planning in the region is low.

From past and current experiences with public hazards awareness programs, six recommendations can be made with respect to these problems:

Recommendation 1: Basic to all public educational efforts in this area is the need to couple hazard awareness information with suggestions about what individuals can do to lessen the risk to themselves and their families.

Without such suggestions for lessening risk to oneself or one's family, information concerning the hazard itself is often not seen as useful and may be forgotten quickly.

Recommendation 2: To make sure that media presentations reach a maximun audience, a high volume of publicity is necessary to attract attention of potential attenders (listeners, viewers, and readers).

If presented by the press, a prominent location in the paper (on the front page, for example) accompanied by pictures may attract readers' attention. If presented on television, a popular or well-known local celebrity (such as a newscaster or weatherman) as host may attract viewers.

Recommendation 3: Regardless of the audience being addressed, scientific concepts must be communicated in easily understandable language and be accompanied by visual aids.

In areas unaccustomed to thinking about the magnitude of damage that an earthquake can generate or about the geologic processes that produce such events, the more graphically these points can be illustrated, the more readily they may be accepted and remembered.

Recommendation 4: In areas unaccustomed to thinking about seismic safety, hazard awareness programs must be long-term.

This would provide the opportunity- for information to be received from several sources, which may reinforce its salience.

Recommendation 5: Earthquake hazard awareness programs must be targeted for specific groups and disseminated through communication channels that are most appropriate to those groups.

For example, the independently-living elderly or the disabled may have certain problems responding to an earthquake event. Programs which include suggestions for how to handle those special problems (e.g., with mobility, or certain physical conditions that require medication) could be presented at senior centers, at health care facilities, through the Veteran's Administration or at Grey-Panther meetings.

Recommendation 6: Individuals need to be given realistic expectations about the amount of assistance they can expect from the local government in the immediate post-impact period.

This is especially important in areas that are likely to sustain regionally devastating quakes since resources are likely to be spread thinly for an extended period of time. Self-sufficiency of households, apartment complexes, and neighborhoods should be stressed to alleviate a belief that the government can handle all emergencies in the immediate post-impact period.

CONCLUSION

These are only a few of the major problems that may be confronted in improving seismic hazard awareness in the Southeast. The recommendations for addressing these problems provide very general guidelines for formulating public education programs. These suggestions will need to be "fine tuned" before they are implemented at the local level by those familiar with the demographic characteristics of the population and with the political and influence structures of communities.

OPINION AS POLICY IN PLANNING, DESIGN AND CONSTRUCTION FOR NATURAL HAZARDS

by

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INTRODUCTION

The successful introduction of design and construction codes and standards for earthquake hazard mitigation depends to a considerable degree upon the attitudes of the staff of public agencies who administer the codes and standards and upon the attitudes of the design and construction professionals who respond to those codes and standards. Rules and recommendations which are regarded as unrealistic by both the enforcement agencies and the public are nearly impossible to implement. Earlier studies have indicated that the public tend to forget the ill effects of natural disasters within a few years after the occurrence. This has been demonstrated in the hurricane regions of the Atlantic and Gulf coasts of the United States. Earthquakes in the Eastern United States have such low frequency of occurrence that the general public regards them with no concern at all.

Field observations (as part of a NSF research grant)[1] in 1979-81 indicated widespread apathy in the Eastern United States[2] in regard to need for seismic design and construction. Multi-hazard mitigation techniques were investigated. It appeared plausible that one might address the issue of seismic design as part of the design process in existence for design of other more common hazards in the region. The premise is sound but the dilemma develops when one realizes that

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[1] "Introduction of Earthquake Hazard Mitigation Through Multi-Hazard Mitigation Techniques in Areas of Low Concern for Seismic Risk" NSF CEE-7926700.

[2] Survey conducted in region from Maryland to Florida

enforcement of codes and standards for common hazards is very erratic; to assume that multi-hazard mitigation would fare any better is unrealistic.

All efforts must begin somewhere. The awareness of seismic hazards are so low that it would appear impossible to introduce a generally applied standard in the region. Probably, the only way to introduce the seismic design standards is as a part of other hazard design standards, but this will require a change in our normal way of doing things.

AGENCY AND PROFESSIONAL ATTITUDES

Interviews and/or field observations were conducted within the following offices in the Eastern United States:

- Building Departments
- Engineering Departments
- Permit and Inspection Departments
- Public Works Departments
- Planning/Zoning Departments
- Division of Civil (Disaster) Preparedness Offices
- Offices of Mayor or Supervisor or Manager of City or County
- Federal Agencies, eq., HUD, TVA, Corps of Engineers, FAA, VA
- Private firms of Architects, Engineers

The objectives were to ascertain the awareness of hazard, hazard design, construction standard, inspection and such issues for the most common hazards in the region and also to ascertain any awareness of the practices related to it. There was no attempt to identify any individual with wrongdoing or any such implications; therefore, the summary will be presented in very general terms.

The impact will be most effective if direct quote or paraphrase of quotes is presented, as follows:

1. Professional Architects and Engineers

- Codes require seismic design but the city/county delete the requirement.

- Architects design a building and then expect the engineers to "engineer" it. This does not afford proper design for natural hazards.

- Professional fees are not adequate for seismic design: maybe fees are o.k. for smaller structures but some increase is needed for larger structures (dynamic analysis).

- Public cannot afford "seismic design," universally applied.

- Seismic (design) is required for primary structure only -- no one ever mentions non-structural components or equipment and furnishings.

- Cost is not that much greater for seismic construction if you start out with it. The extra cost is more in the late decision to change from standard construction to seismic half way through.

- Confusion in the building (inspection) department regarding "tie downs".

- Major problem is lack of experienced people in the inspection department (regarding hazards).

- Seismic is required by (some) military, gas storage, HUD (elderly), National Park Service (?).

- We don't do it if it's not required (by authorities or owner).

- Most people just don't care.

- Cost is primarily in non-structural conponents and equipment: Not in primary structure.

2. Agencies (Engineering, Code, Inspection, etc.)

   - We are in Zone 2 and 3 but we don't enforce "seismic".

   - Problems are "zoning", not the building codes.

- Most super-structures are designed for seismic.

- Old construction is the real problem -- a major quake would destroy 90% of the city.

- Many areas have no concern for "tiedowns".

- Our (my) major concern is hurricane and seismic but people are not interested. There is a gradual increase in concern.

- Not good coverage of disaster issue in news media.

- We have growing jurisdiction (by annexation) with no increase in staff.

- Understaffed. Rely on certifications by the architect or engineer; little or no inspection on most projects. Federal Flood Insurance Program! Currently enforce standards for "high water"--especially mechanical and electrical.

- The electrical transformers are on the ground and the buildings are elevated! Does this make sense (with Federal Flood Insurance Program)?

- Lack of zoning and subdivision ordinances. We control through building permit only.

- No mention of seismic concern (in my region).

- Low regard for professional services in the state! Low esteem.

- Lack of location maps for underground utilities.

- Problem is buried propane/gas tanks without "tiedowns".

- Foundation erosion -- water scours earth away from pilings. Code does not address the issue.

- Occasional problem -- the handicap code requires violation of "high water" code (Flood Insurance Program). All the department can do is keep occupancy out of lower levels.

- Problem is keeping and maintaining protection against storm surge. "Breakaway walls" code is not rigid enough.

- I'd be d-----if I'd ever let anyone waste their money designing for an earthquake that will never happen. I don't know of a single person who even remembers the last one.

3. Agencies (Planning, Zoning)

- Present trend toward looped supply systems, if enough money is available.

- Need early start in comprehensive planning and zoning ordinances in new, growing communities.

- We'd suspect that people would feel the federal government is crazy to study earthquake problems in the Carolinas.

- . . . upset with Federal Disaster Teams:

- Fantastic duplication of service -- every agency has to question the same people.

- Poorly organized

- Gross waste of dollars

- Lack of understanding of local issues

- No one has ever found a cause for the 1886 earthquake!

- Lack of agency co-ordination: some developments are without planning input - bridges, egress, fire, police, traffic control, etc.

- No design standards for seismic.

- Major concern is flooding.

- Federal Flood Insurance Program is only control now. Livable floor above high water is only enforcement now.

- Height limitations are aesthetic - not based on safety.

4. Agencies (Civil Preparedness/Disaster Preparedness)

- Lack of effective control through zoning and planning; control is through building permit only.

- Reasonable cooperation with Council of Governments.

- Reasonable cooperation with Federal Agencies (TVA) in flood control.

- Excellent cooperation with Volunteer Fire Departments.

- Too many counties do not have their own (preparedness) plans -- they rely on the State!

- Need good back-up systems.

- Federal Disaster Teams a real questionable value: They don't know local issues and duplicate services; should use regional "Civil Preparedness Agencies" - to give experience to others to better prepare them to aid themselves in future.

- . . . . Plans are good for all disasters -- even if it doesn't mention earthquakes.

- . . . core is "volunteer": ham radios, 4-wheel drive vehicles, volunteer fire departments.

- Most people don't know about Disaster (Civil) Preparedness Agencies.

- Many areas have little or no requirement for tie downs...or for seismic!

- Federal Flood Insurance Program is usually the only control mechanism.

- . . . . Lots of poor construction! Bridges are a real problem.

- No specific mention of seismic in evacuation plans - same as hurricane and flood. Plans are for post-disaster: evacuation, rescue, clean-up, etc.

5. <u>Agencies (Federal)</u>

- Cost is the same for "seismic" and "non-seismic" so we design all of them "seismic".

- Use seismic for large dams only. All major dams require seismic.

- Use regional codes for lateral forces.

- Require that local/regional codes be followed. (If local authority modifies the code, it is still the local code.)

OBSERVATION AND RECOMMENDATIONS

The recognized natural hazards in the study region were hurricanes, storm surge, and flash flood (and some tornado and thunderstorm-lightning-fire) as most related to building design and planning. Only the rare public official or professional recognized earthquakes as a natural hazard. The expectation that buildings codes and zoning ordinances and their proper enforcement would provide successful hazard mitigation for the recognized hazards is in serious need of support. The recognized hazard is not taken too seriously! What chances do we have that the unrecognized "seismic" hazard will ever be taken seriously?

1. The general success of the Federal Flood Insurance Program may be one significant clue out of all the observations made during the study. The people responded when their pocketbook was affected! The acceptance of this federal program should be noted by all other agencies affected by natural disasters. The public has grown to expect that the federal government is the insurer of last resort. It is reasonable to expect that one cannot continue to be irresponsible and expect a federal bailout at taxpayers expense, even in a natural disaster. Research into such a general program is needed.

2. Education of the architect and engineer is beginning to address the technical and ethical issues of hazard design. FEMA, NSF, American Institute of Architects (AIA) Foundation and other agencies have begun extensive workshops and seminars to introduce hazard design to these critical professionals. Hopefully, the curriculum will begin to reflect the training these professional educators have received. Additional work is needed to bring the practicing professional up to standard through continuing education programs.

   The same effort is now needed for the people who staff middle and upper executive positions in local and regional governmental agencies. Those agencies which were positively and creatively addressing the issues were usually under the leadership of a manager who knew the problems and was sensitive to them. A substantial number of professionals in the area felt that the "building official" was the place to start a major change in hazard mitigation.

3. The observation of some that "the public cannot afford a seismic code, universally applied" is another critical factor in hazard mitigation. Research is critical in this area to identify the possibility of "life safety" and and "cost-benefit" priorities being established for certain building types and functions. The hospital emergency, police, fire, communication center, etc., may have critical needs for post-disaster activity. Many other buildings may well be permitted to suffer damage with the cost of repair less than the cost of construction and/or maintenance.

4. "Self-protection" education is critical in areas such as traffic safety, fire safety, drug and poison control, etc. It is also a critical factor in life safety and life-loss control in natural disasters. Much of the loss of life could be prevented if the people involved knew what to expect and what they could do to save their own lives.

The National Safety Council has conducted major educational programs regarding traffic safety. They now are considering the environmental safety issue. Some similar programs regarding natural hazards is now essential. We cannot design a fail-safe environment for life safety in the natural hazards. Self-protection education is necessary. National and local TV, radio, newspaper should address these issues as a service to the Elementary and Secondary school programs are also needed.

5. The code and ordinance itself was identified by many to be weak, or not specific enough or lacking in some way. The model codes and the local option codes are all in need of clarification and expansion to address the issue of natural hazard design and construction.

   There is always the problem of the model code being too general and relying on local options to pick up specific issues or to refer to other special national standards which may not have special, specific or regional application. Model codes can be too regional, also, which makes their application difficult if not impossible, in some regions not characteristic of the home base.

   The political and ecnomic factors involved in model codes is very complex but some attempt should be made to identify a fitting and proper regional code as a model for a particular region.

EARTHQUAKE HAZARD PREPAREDNESS IN THE SOUTHEASTERN UNITED STATES: A PATIENT REVOLUTION

by

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INTRODUCTION

The Southeastern United States is not prepared to cope with the social and economic impacts from either a recurrence of a major earthquake like that of 1886 in Charleston, South Carolina or 1811 in New Madrid, Missouri or from smaller damaging earthquakes. This situation is particulary critical to the public. When seismic hazard is considered in a reasonably broad time period, significant potential of earthquakes to cause death, injury and damage in the Southeastern United States is apparent as it is in southern California and parts of other Western States. While western earthquakes occur more frequently, it is apparent that the destructive capability of eastern earthquakes ranks the southeastern seismic hazard with that of the western region.

NATIONAL IMBALANCE OF SEISMIC SAFETY PROGRESS

National seismic safety technology and program policy advancements generally have been limited to the western region of the United States. Noteworthy seismic program developments in Massachusetts are apparently the only exception. Certainly, much of the basic technology and experience developed in these other States is applicable to the Eastern States. However, they remain basically as potential improvements not yet effectively applied in the southeastern region. Consequently, a considerable imbalance exists between the earthquake damage reduction and mitigation postures of the Eastern and Western United States. Southeastern seismic safety developments remain those common to California several decades ago. In September 1981, a national conference and associated regional workshop were held in Knoxville, Tennessee to address this imbalance. Many of us here attended that early conference. The conference marked a first time that engineers, geologists and planners assembled in a major conference to discuss the many important issues related to earthquake hazards in the Eastern United States. In my view, it was the first major breakthrough in seismic technology and experience transfer to this region. The over six hundred people who participated reflected wide felt concern of the public as well as technical and political communities. Most of the participants were from the Eastern States.

Significant professional contributions to the seismic technological needs of the Southeast United States have been made. Some of these are continuing, whereas still others are relatively new developments. The latter include the many noteworthy seismic safety initiatives launched at the Knoxville conference, such as the Southeastern United States and South Carolina Seismic Safety Consortiums, as well as this conference. I believe that most of these excellent developments are products of many of our conference participants. However, despite these valuable actions and those of numerous city, county, state and federal disaster planners, the Southeastern United States remains unprepared to cope with the social and economic impacts from either a recurrence of a major earthquake or smaller damaging earthquakes.

Progress has been woefully inadequate in seismic hazard reduction and mitigation throughout the entire Southeastern United States. This includes that of public policy developments regarding seismic safety. Even more disturbing is the unchanged persistent need to establish at least minimum knowledge at all professional and public levels, adequate for the establishment of seismic safety policy and the maintenance of it once established. Seismic technology and policy developments are mutually dependent. Achievements in one are prerequisite to opportunities in the other. In sober realization of these factors and with developing federal support and encouragement, significant effort is gaining momentum in this region to meet the grave seismic hazards facing our communities. Our general objectives are twofold. First, we are striving to increase regional technical knowledge and capability through regional technical developments as well as technology and experience transfer from our sister Western States. Building upon this base and increased public awareness, our second objective is to achieve public adoption of effective seismic policy. Our approach is fundamentally different in that broad community level involvement is being developed prior to seeking the legislative mandating of seismic policy. This "grassroots" approach is to accelerate technology transfer to the lowest levels and to insure public acceptance of seismic safety legislation once enacted.

We understand the effort will require considerable commitment of time and resources, including that of the federal government. However, the dire risk to the safety of our public leaves no responsible alternative. The following sections of this paper describe seismic safety program organizations and developments in the Southeastern United States. They emphasize the integrated support needed and suggest means of insuring adequate coordination of such support.

PROGRESS ORGANIZATION

During workshop sessions at the 1981 Knoxville conference, a draft 5-year action plan was developed for improving earthquake preparedness and mitigation in the Southeastern United States. Concurrently, regional attendees established the Southeastern United States Seismic Safety Consortium (SEUSSSC) and appointed an Ad Hoc steering committee to guide its continued development. The SEUSSC is to serve as the entity to refine and implement the recommendations of the draft five year action plan, evolving a seismic safety policy for the Southeastern United States achieved through coordinated but independent state seismic programs.

The South Carolina Seismic Safety Consortium (SCSSC) was organized to develop and influence the implementation of a five year comprehensive action plan for earthquake preparedness and mitigation in South Carolina with emphasis on its "low country" region. This effort builds upon the draft five year action plan developed at the Knoxville Conference and Workshop. The SCSSC includes approximately seventy (70) representatives from government, industry, professional associations, universities and the private sector. This consortium is serving as the prototype state program for other state consortiums in the Southeastern United States, all of which are to be ultimately integrated for coordination under the newly developed Southeastern

United States Seismic Safety Consortium. Figures 1 and 2 illustrate this organization.

The South Carolina Seismic Safety Consortium has three major objectives. They are:

a. To develop and influence the implementation of a comprehensive state seismic safety policy insuring adequate earthquake preparedness and mitigation in South Carolina with emphasis on its low country region,

b. To provide synergism and technical qualification among engineers, geologists, seismologists, planners, governmental leaders and the public as necessary to insure adequate sustained implementation of seismic safety policy, and

c. To insure federal and state seismic research and development programs adequately address the technical needs of South Carolina and the Southeastern United States.

CERTAIN PROGRAM INTITIATIVES

Several basic program actions are considered essential to achieving minimum adequate earthquake hazard preparedness in the Southeastern United States in the next 5-10 years. These are listed in Table 1 and discussed below.

1) Establish Other State Seismic Safety Consortiums/Commissions

The South Carolina Seismic Safety Consortium has served as a prototype for other similar consortiums to be established in the other Southeastern States which are subject to significant seismic hazard. These other state seismic safety consortiums now need to be established. In addition to directly improving preparedness in the individual states, these state organizations would collectively greatly enhance the technology and experience transfer the Southeastern States are in need of. Development of new technology would also be enhanced.

TABLE 1
PROGRAM INITIATIVES

ESTABLISH OTHER STATE SEISMIC SAFETY CONSORTIUMS/ COMMISSIONS

ESTABLISH ADEQUATE TECHNICAL BASELINE THROUGHOUT THE SOUTHEAST

PROMOTE VULNERABILITY STUDIES THROUGHOUT THE SOUTHEAST

ESTABLISH TECHNOLOGY TRANSFER AND DEVELOPMENT COUNCIL (TTDC)

SEISMIC UPGRADE OF EXISTING BUILDINGS

DEMONSTRATION OF TECHNICAL DESIGN PROFICIENCY

AMERICAN SOCIETY OF CIVIL ENGINEER'S ACCEPTANCE OF SEISMIC RESPONSIBILITIES

COMPLETE DEVELOPMENT OF THE SOUTHEASTERN UNITES STATES SEISMIC SAFETY CONSORTIUM

Prompt organization is recommended considering the developing momentum of certain regional technology acquisition efforts and the significant time required to establish an effective statewide seismic safety organization.

2) Establish Adequate Technical Baseline Through the Southeast

Technical information and training regarding seismic related technology are very limited throughout the Southeastern United States. Broad improvement is necessary for the development and maintenance of adequate seismic safety policy. Several initatives are currently being developed. First, a centralized regional seismic reference center is essential. None exist throughout the entire Southeastern United States. Second, regionally unique technical requirements exist. Regional seismic research and design development activity needs to be dramatically increased among the commercial as well as educational sectors. Training and experience derived from such technology acquisition would directly benefit the regular practitioner and public. In this regard,

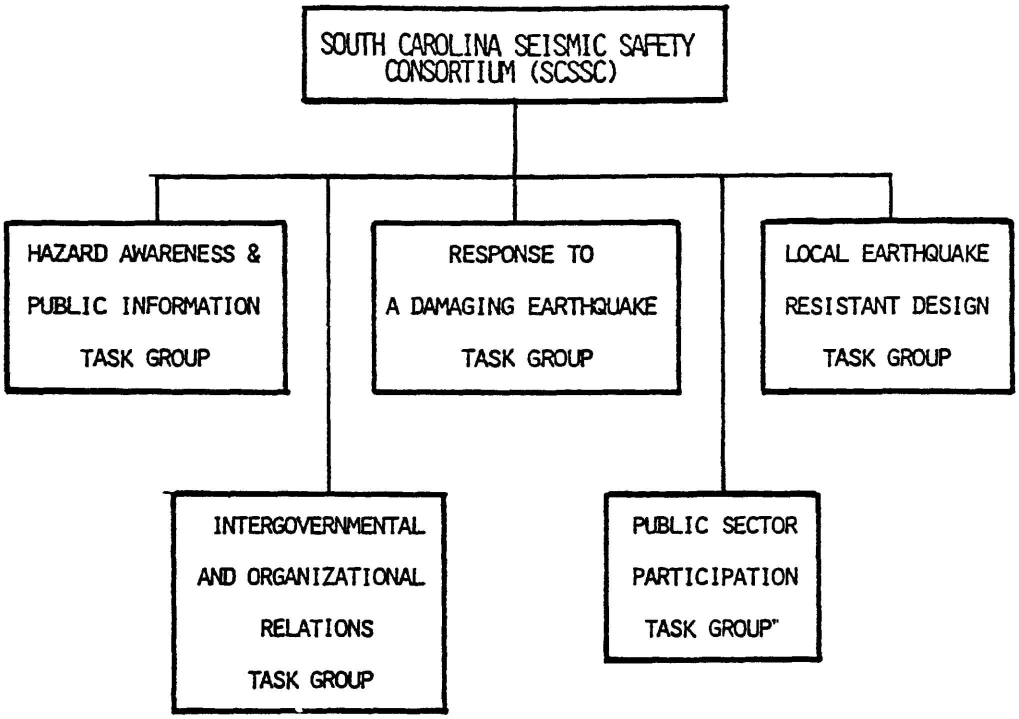

Figure 1.--Organization of The South Carolina Seismic Safety Consortium

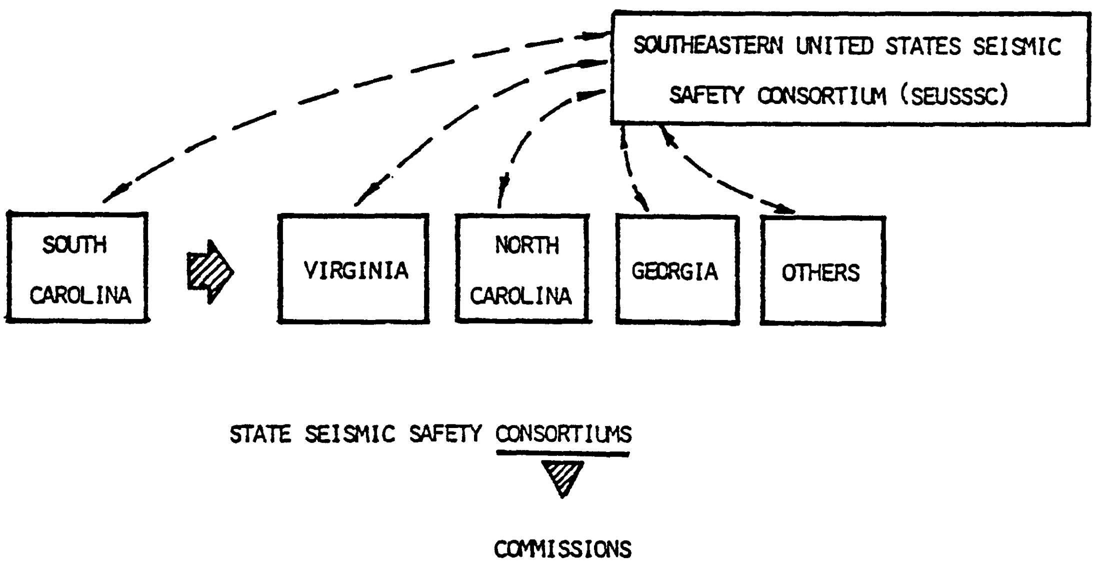

Figure 2.--Interelation of The Southeastern United States Seismic Safety Consortium with various State Consortiums

significantly increased Earthquake Engineering Research Institute (EERI), FEMA, USGS and National Science Foundation support is mandatory. Third, seismic design instruction needs to be routinely offered in regional engineering centers. Fourth, much of the limited seismic design accomplished is the product of non-regional or western professionals. These opportunities in design and experience growth are being lost for local engineers. At least minimum participation by local engineers in all regional seismic design projects should be mandated.

3) Establish Technology Transfer and Development Council (TTDC)

As the federal government and our western counterparts proceed to upgrade seismic building code provisions in line with the "Tentative Provisions for the Development of Seismic Regulations for Buildings" (ATC 3-06), prepared by the Applied Technology Council, the Southeastern United States wrestles in near obsolecence with the acceptance and implementation of the now aging seismic provisions of the Uniform Building Code (UBC) or the Standard Building Code (SBC). A major impediment has been the virtual absence of Southeastern representation on the Applied Technology Council. Of the ninety (90) project participants identified in the ATC 3-06 report, only two are from the Southeastern United States, both from Memphis, Tennessee. Usually, code development and acceptance require a considerable amount of time. However much utility is realized throughout the development process by the participants as they engage in continuing deliberations. Through them, community technology can normally be upgraded years ahead of final code adoption. This benefit has not been realized by the southeastern region, as it essentially has not been a participant. Wide concerted efforts are now being charted elsewhere to guide community acceptance of the more updated tentative code provisions. On the other hand, the Southeast continues to encourage effective implementation of standard UBC and SBC code provisions.

On this major issue, seismic safety advancements within the Southeast depend heavily upon strong support by the Center for Building Technology of the National Bureau of Standards and the National Science Foundation. Specifically, a Technology Transfer and Development Council (TTDC) should be established and maintained in support of the Southeastern United States Seismic Safety Consortium to effectively transfer ATC 3-06 baseline technology to the southeastern region. As currently proposed, this group will have more broad responsibilities. First, it is to insure the effective and timely transfer of existing and future technology developments into the southeastern region. Second, it is to encourage and coordinate the development of technology addressing unique regional needs. This development should be done largely by the southeastern technical community. Third, the TTDC will serve as a technology reference center for the Southern United States.

Like the Applied Technology Council (ATC), the council is to consist of a full time technical staff and a board of directors. Members of the initial board of directors are to include two technical representives from each of the following states; Georgia, North Carolina, South Carolina, Virginia and Tennessee. Representation from EERI and ATC will be requested.

4) Promote Vulnerability Studies Throughout the Southeast

Probably, one of the most important keys to successful public seismic safety policy is the community vulnerability study. The vulnerability study assesses the local earthquake hazard, and, considering the damage susceptibility of existing facilities and systems, determines the extent of probable community damage resulting from a likely seismic event. From this determination, the impact on the community is quantified in terms of killed or injured people, reduced critical services, etc. The current critical need for such studies in communities throughout our region is reflected in a recent letter to me by Mr. Thomas L. Hansen, Executive Director, Council of Governments Berkeley, Charleston and Dorchester Counties in South Carolina. His statement is simple but profound in that it captures public sentiment common in the Southeastern United States. It underscores the urgency of the vulnerability study in achieving code adoption, improved disaster preparedness and other seismic safety advancements. Mr. Hansen wrote, "Personally, I believe that most people in this region are aware of the fact that a major earthquake could occur at any time. I do not believe that they are aware of either the possible damages that could occur as a result of a major episode or of what may be done to mitigate damages."

Vulnerability studies have been concluded for only four cities in the entire United States; San Francisco, Los Angeles, Puget Sound and Salt Lake City.

Several other cities in the Central United States have initiated studies. In all cases, these studies have been led and largely conducted by visiting consultants and other technical study personnel. The SCSSC and The Citadel in Charleston, South Carolina, have commenced the first such vulnerability study in the Southeastern United States. Its project director is Colonel Maurice R. Harlan, a faculty member in the Department of Civil Engineering at The Citadel. With valued FEMA support, this vulnerbility study is being done for Charleston, South Carolina. It is to serve as a prototype for the Southeastern United States. Unlike all others, this study is being done by local people. The intent is to retain locally the technical experience that only comes from direct participation, to minimize study costs allowing more communities to likewise benefit and, finally, to produce a preliminary "vulnerability study handbook" for use by other regional communities. Significant technical assistance has been donated to-our local vulnerability study team by several national consultants. They included Dr. Samy A. Adham, Agbabian Associates, Los Angeles, California; Mr. Henry J. Degenkolb, H. J. Degenkolb Associates Engineers of San Francisco, California; Dr. Winfred O. Carter, Utah State University, Logan, Utah; and Dr. Anschel Schiff, Purdue University, W. Lafayett, Indiana.

Certainly, the vulnerability study is emerging as a necessary element for a community's earthquake preparedness and hazards mitigation. I believe the Multi-Protection Design Summer Institute Emergency Management Institute of FEMA located at Emmitsburg, Maryland, should play a major role in the evolution. It should provide more wide spread service to engineers in the Eastern United States. More importantly, its curriculum should be expanded to include instruction to community engineers in the proper conduct of vulnerability studies. Instructional material should include technical handbooks on how community engineers can direct vulnerability studies. Only through such important measures will most communities be able to benefit from these evaluations.

5) Seismic Upgrade of Existing Buildings

Seismic strengthening is largely ignored in the restoration of old and historic buildings throughout the Southeastern United States. This is of particular concern since the buildings are largely of unreinforced masonry construction and were of little seismic strength even when constructed decades ago. Due to age and weathering, they are even more inadequate today. Builders, developers, the public and regional engineers need to be instructed in the economically feasible seismic strengthening measures possible within available technology that are consistent with their historic character. Certainly, historic buildings can be seismically strengthened without compromise of their historic character. Certainly, they must be. Otherwise, the public is deceived into assuming these often compromised facilities are stable for years of safe future service. The correction of this condition can be encouraged through the federal historic restoration agencies that administer tax credits to those restoring such historic buildings. In review processes, compliance with applicable federal seismic upgrade provisions should be made prerequisite to tax credit allowances just as the more superficial aspects are mandated today. It seems unreasonable that some agencies of federal government fully understand the means and imperative need to strengthen such old buildings while other federal agencies freely administer such government subsidized restorations without dictating such precautions. In any event, procedures like that developed in Los Angeles for the practical seismic strengthening of old unreinforced masonry buildings have not yet been introduced and adopted in the southeast. The need is imperative.

6) Demonstration of Technical Design Proficiency

Very few engineers practicing in the Southeastern United States have been adequately trained in earthquake engineering. No state professional engineering examinations include seismic design exercises. These professional certification processes should more adequately protect the public welfare. Tests should be revised to include earthquake engineering principles and procedures. In the meanwhile, an appropriate prescribed short course in seismic design should be offered to promote technical sufficiency. Both measures are employed among the western states.

7) American Society of Civil Engineers Acceptance of Seismic Safety Responsibilities

Civil engineers are largely responsible for the public's environment and, hence, seismic safety. Civil Engineers rightfully played a leadership role in the development of Massachusetts' seismic safety code, the only such state code in the Eastern United States. Members of the Southeastern United States Seismic Safety Consortium are acting to encourage southern civil engineering state sections to form seismic safety technical groups and assume a lead role in advancing state policy. South Carolina and Georgia Civil Engineers have recently accepted these responsibilities. Other relevant technical professional organizations should likewise participate.

8) Continued Development of The Southeastern United States Seismic Safety Consortium

CONCLUSIONS

The major accomplishments in earthquake hazard reduction and mitigation achieved under the provisions of the National Earthquake Hazard Reduction Program have not yet materially benefited the Southeastern United States. Seismic safety developments remain those common to California several decades ago.

This situation is particularly critical to the public in the southeastern region as there is as great a potential of earthquakes to kill and damage in the Southeastern United States as there is in southern California and parts of other Western States. While western earthquakes occur more frequently, it is apparent that the great destructive capability of eastern earthquakes ranks the southeastern seismic hazard with that of the western region.

Significant effort is required to meet the grave seismic hazards facing the southeastern communities. A concerted program has been launched by the Southeastern United States Seismic Safety Consortium in concert with the South Carolina Seismic Safety Consortium to bring the southeastern region abreast of California and other leading Western States in regard to effective earthquake hazard reduction and mitigation. This effort will require considerable commitment of time and resources, including that of the federal government. However, the dire risk to the safety of our public leaves no responsible alternatives to the patient seismic safety revolution now in progress. The full support is necessary of the National Science Foundation, United States Geological Survey, Federal Emergency Management Agency, the United States Nuclear Regulatory Agency and the National Bureau of Standards (Center for Building Technology). The program demands are broad and involve the specific specialized responsiblilites of each of these agencies. With this essential assistance and that of our considerate colleagues in the western regions, reasonable levels of seismic safety can be achieved in the Southeastern United States - and must be.

MULTIHAZARD PILOT STUDY - AN INTEGRATED APPROACH TO EMERGENCY MANAGEMENT

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INTRODUCTION

The Federal Emergency Management Agency (FEMA) was created in 1979 to serve as a single point of contact within the Federal government for emergency management activities. FEMA assumed the various roles assigned to her predecessor agencies. Included was the responsibility to manage hazard-specific programs that had developed piece-meal. Thus, FEMA found itself responsible, with regard to natural hazards, for leadership in floodplain management, the national earthquake hazard reduction efforts, dam safety, and other hazard-specific hazards. Additionally, some programatic "successes" have been unique... or possibly just curious. In fact, one such success story presented in the following few paragraphs illustrates the flaw in hazard-specific emergency management planning.

About 85 percent of the population of Utah resides on or near the Wasatch fault. In recognition of the earthquake hazard some officials began efforts to mitigate the impacts. The emergency room of an existing hospital, which was above the elevation of expected flooding, was found wanting when checked for tolerance to earthquakes. A planned addition to the hospital was modified to accomodate an emergency room in the seismically qualified basement. Thus, the public was assured an emergency medical treatment facility.

It is understandable that the local officials were happy with their accomplishments. They had, on one hand, a treatment facility which would survive floods as bad as any experienced in the area. If it were destroyed by an earthquake, the other hand contained a facility which would survive...and vice-versa. Overlooked, in their zeal, were several large dams just east of the city; high in the Wasatch Mountains. There is no evidence which would lead one to believe that any of these dams would survive a catastrophic earthquake.

Thus, when the big earthquake comes and knocks out the flood resistant facility the town will have their earthquake resistant facility...for about 30 minutes; just long enough for the flood wave from the failed dam or dams to reach it. Emergency action planning, effected by hazard-specific "blinders", produced what may well be a totally ineffective medical facility following an event for which it was supposedly designed. It is not surprising that this situation is repeated elsewhere.

THE MULTIHAZARD APPROACH

The potential for ineffectively using resources, as one hazard-specific problem after another is resolved, is too great. Therefore, FEMA has initiated a "multihazard" approach to emergency management. The purpose of this approach is to ensure that plans and programs do not overlook threats to the health and safety of the public and that resource management efforts take advantage of similarities in crisis scenarios and do not overlook unique aspects of specific hazards.

As currently envisioned, a multihazard emergency management approach would require the following steps.

- o Assess the study area and its hazard characteristics. ("Study area" is intended to include both land, property and population.)
- o Involve inter-and intra-governmental authorities.
- o Characterize the impacts of historical hazards events.
- o Assess the universe of hazards and potential for occurence in the study area.
- o Assess the multihazards and impacts on the study area to identify similarities and unique issues.

- Analyse vulnerability to prioritize hazard.
- Develop and implement instrumentation and warning strategies.
- Develop, or modify existing, emergency reaction plans to accomodate the common, and unique, aspects of the multihazards selected.
- Develop mitigation and preparedness strategies and plans.
- Develop and deploy public awareness material.
- Test.

At the local level (the County Commissioner, sheriff or whoever has the emergency response authority) these actions tend to be handled in an integrated, or multihazard, manner. After all, there is usually only one person dealing with the problems. However, at the regional, State or Federal level, things tend to become more specialized. It becomes necessary to consciously establish the multihazard approach in the emergency planning efforts.

To accomplish this, FEMA has embarked on a pilot multihazard emergency management project in cooperation with the State of Utah. The project is to provide a model for the assessment of multihazards and provide a real-world test of the approach. It was noted early in the effort that important players were not communicating. Significantly, the existence of data and information acquired by one group was unknown to others. Therefore, a panel of State Agency and Federal agency personnel has been formed to provide a coordinative and oversight function.

A model is being developed to guide consideration and appraisal of hazards as they may impact the area with subsequent assessments of existing emergency plans and identification of necessary modifications. The program is on schedule with development of the model anticipated by mid-year. The model will be applied to counties and communities in the study area. Ultimately the mitigation and preparedness plans for the study area will be upgraded to respond to the multiple-hazards which threaten the public.

THE INTERGRATED EMERGENCY MANAGEMENT SYSTEM

The "multihazard program", originally envisioned as dealing with natural hazards, is a logical part of a new management approach. The balance of this section is extracted from a memorandum from the Director of FEMA dated May 10, 1983.

FEMA has reviewed its experience with the range of programs managed by the Agency and those for which FEMA has a coordinating role among other Federal agencies that have lead responsibilities in preparedness and response. Based upon this review, FEMA has embarked upon an improved method for implementing its programs, the Integrated Emergency Management System (IEMS). The IEMS concept applies to all levels of government, all hazards, and all phases of preparedness, mitigation, response and recovery.

IEMS stresses an integrated approach to management of emergencies across the full spectrum, including natural disasters, such as tornadoes, hurricanes, floods, and earthquakes; technological disasters, such as explosions, release of hazardous materials, accidents involving radiological materials, and possible nuclear power plant accidents; resource shortages; and possible attack. There are varying levels of common requirements across this emergency spectrum and IEMS will stress the preparedness elements common to emergencies across the full spectrum, what at the same time recognizing elements unique to specific types of emergencies. The larger emergencies associated with a catastrophic earthquake or war will be accorded special attention and greater Federal involvement. Initial emphasis will be placed on basic emergency preparedness capabilities--planning, warning, communications and control and identification of resources required for emergency response--in particular, at local levels, where the people live who must be protected from emergencies across the entire spectrum.

IEMS will, therefore, provide for an integrated approach to preparedness for all emergencies, in line with FEMA's purpose and charter. General principles applying to the developing of IEMS include providing maximum flexibility to State and local governments in achieving commonly accepted Federal, State, and local goals, as well as integrating emergency management planning into mainstream State and local government planning and decisionmaking processess.

IEMS will also focus on the integration of Federal Preparedness programs, on improving coordination among the Federal agencies involved in the response to various emergencies, and on the linkage between Federal Preparedness programs and State and local preparedness in such areas as resources management, continuity of government, and resource mobilization for major domestic and national security emergencies.

CLOSURE

The multihzard pilot program will provide an excellant opportunity to determine how a broad spectrum of natural hazard can be brought under one umbrella and evaluated concurrently. Subsequently, the natural hazards program will join technological hazards and attack scenarios to form an integrated approach to hazards management.

The pilot program will not be limited to just Utah. We look forward to working with at least one other State to broaden the number of hazards which must be considered. The State of South Carolina may be a prime candidate. As other speakers have noted, the State is rich with potential damage from hazards. Floods, hurricanes, tornadoes, unsafe dams, and nuclear facilities must all eventually be integrated in an emergency management system. Only in this way can the public receive the obvious benefits of a comprehensive emergency management approach.

THE UTAH SEISMIC SAFETY ADVISORY COUNCIL

by

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INTRODUCTION

The Utah Seismic Safety Advisory Council was established by Legislative Act in 1977 and charged to recommend a consistent public policy framework for earthquake hazards in Utah. The council completed its work in 1980.

UTAH'S EARTHQUAKE ENVIRONMENT AND HAZARDS

Earthquakes in Utah are historical fact. Since settlement of the State in the mid-nineteenth century, a continuous history of earthquakes has been observed. Severe and damaging earthquakes are expected in Utah in future years, although one can only estimate their locations and strengths. Utah's settlement pattern has an unusual correlation with the region of greatest earthquake activity, and more than 80 percent of the State's population and development lie within a zone along the Wasatch Front that defines the region of greatest earthquake hazard.

The damaging effects of earthquakes, and thus their threat to life and property, impact principally upon the works of man. The concerns of earthquake safety therefore are focused upon where we build and what we build. Utility systems, roads, and dams, as well as buildings, are among the facilities that could be detrimentally affected.

EARTHQUAKE SAFETY DEFICIENCIES

Facilities in Utah are expected to be damaged by future earthquakes. Property losses assuredly will result from these earthquakes; the extent of resulting life loss and injury will depend upon unpredictable factors of earthquake strength, location, and quality of construction of facilities.

Earthquake resistance traditionally has not been considered in facilities designed and constructed in Utah. Older facilities generally are vulnerable to earthquake forces, as are many facilities constructed as recently as the 1970's. Standards for construction that include earthquake safety provisions continue to be ignored or rejected, even today.

Two types of deficiencies exist in Utah. The first deficiency concerns the need for broader consideration of earthquake safety in new facilities so that the inventory of unsafe or marginally safe facilities is not enlarged as the State grows. The second deficiency is the degree and nature of earthquake risks in existing buildings, utility systems, dams, etc.

Each of the two types of deficiencies have different remedies. The first deficiency results from lack of standards, guidelines, and adequate procedures in the planning and review of new facilities. The second deficiency, a result of past decisions, can be remedied only within the facilities themselves through some sort of abatement effort.

COST CONSIDERATIONS

Earthquake hazards in Utah pose an unavoidable cost. Hazards mitigation entails a cost; so does a decision to do nothing about the problem. The cost of mitigation occurs in the construction of stronger facilities. The cost of doing nothing looms in the future when the inevitable earthquakes occur and cause losses.

Both types of costs can be effectively managed, but neither can be eliminated. Management of the cost of mitigation requires that prudent policies be promulgated involving standards and procedures in design and construction of buildings and other facilities, policies that everyone should be required to follow. Management of the cost of earthquake damage to existing facilities entails carefully drafted policies of selective hazards abatement, dealing first with conditions of highest hazard.

Policies recommended by the Seismic Safety Advisory Council were developed using benefit/cost analyses from which the most cost-effective remedies are selected. Detailed risk assessments of existing facilities reveal that earthquake hazards abatement is cost-effective only for special situations in Utah. These situations require greater discussion than can be provided in this summary, and the reader is referred to the detailed studies for specific cases.

RECOMMENDATIONS

As the foundations of a comprehensive and coordinated earthquake safety program for Utah, the Seismic Safety Advisory Council made the following general recommendations:

1) Adopt legislation requiring compliance with earthquake safety provisions of the building code.

2) Amend planning statutes to provide explicit authority for local governments to plan for earthquake safety.

3) Accelerate the State seismic risk mapping program to achieve completed mapping of the major risk areas within five years.

4) Adopt legislation requiring that siting evaluations of geologic hazards be made for all public-use facilities.

5) Enforce earthquake safety code provisions in facilities under State jurisdiction.

6) Establish seismic standards and review procedures for dams and reservoirs.

7) Strengthen licensing laws for architects and engineers to improve professional accountability.

8) Assist local governments to strengthen building code enforcement practices.

9) Promulgate and enforce standards concerning the earthquake resistance of public utility systems.

10) Promulgate guidelines and procedures within the Department of Health to reduce the earthquake risk to water supply and waste disposal systems.

11) Utilize regulatory authorities now available to ensure that new schools and health-care facilities meet appropriate earthquake safety standards.

12) Undertake a program of selective retrofit or replacement of high-hazard facilities that are essential in our communities or that have large occupancies of people.

13) Encourage local governments to safeguard fire equipment from operational dysfunction due to earthquake through assistance from the State Fire Marshall's office.

14) Develop and implement abatement programs leading to eventual elimination of existing high-hazard, publicly occupied facilities.

15) Identify and correct conditions in water supply systems that are vulnerable to earthquake damage.

16) Provide secure and reliable communications systems for post-earthquake response and recovery activities.

17) Establish a strong-motion instrumentation program to obtain needed information about earthquake-induced ground motions in Utah soils.

18) Establish an earthquake safety office for the purpose of providing overall coordination and direction for earthquake safety in Utah.

GOALS CONCERNING EARTHQUAKE HAZARD AWARENESS

by

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INTRODUCTION

Charles Darwin, upon witnessing the disaster that took place in Chile in 1835 from a major earthquake, had this to say: "It is a bitter and humiliating thing to see works which have cost man so much time and labor overthrown in one minute." An earthquake threatens not only buildings but transportation, utilities, and communications networks on which our urban population depends.

EARTHQUAKE HAZARD AWARENESS

In reviewing the current state-of-hazard awareness in the Southeastern United States and the Charleston area in particular, it is evident that except for a few public officials and key utility personnel, there is no public awareness of a potential disaster from an earthquake. Interest in earthquakes by the public has increased in recent years because of new articles on hazard awareness and the Mt. St. Helens disaster, however, the public in general feel that a major earthquake will not happen in the Southeast.

As with other types of disasters (hurricanes, tornadoes, and floods) the public tends to rely on local, State and national disaster preparedness officials to plan, implement, alert, and in general take care of them if a disaster should occur. A tremendous amount of faith and trust is placed in these officials by the public to provide the necessary planning and protection from a disaster.

People tend to forget that the scientific community cannot predict with any great accuracy where and when an earthquake will occur. It is conceivable that one day this will be possible, thus, providing a means of increasing the hazard awareness of the general public.

PROBLEM - PUBLIC APATHY

Public apathy is our number one problem to overcome in earthquake hazard awareness. How can we make others aware that a major earthquake could occur and cause considerable damage to property and loss of life? The majority of participants in this workshop understand the importance of hazard awareness and realize what will happen should a major earthquake occur in this area tomorrow. What can we do as participants in this workshop to lessen the impact, thus reducing the loss of life and property?

LONG RANGE GOALS CONCERNING EARTHQUAKE HAZARD AWARENESS

To heighten hazard awareness in the Southeastern United States, we can look to other areas in this country and around the World for guidance and assistance in emphasizing hazard awareness activities, and once these activities are made known to the public, hazard awareness should increase. The following are examples of activities that can be undertaken by various agencies:

1) Cities should develop their own municipal disaster plans. These plans should be coordinated with existing county, State, and Nation plans to provide the maximum flexability between the agencies involved and to avoid a duplication of effort. In areas where there are large military installations and National Guard units, the use of their personnel and equipment should also be coordinated.

2) Cities and counties should develop regulations and guidelines pertaining to building codes and land use management, using earth-science information as a guideline. There is no doubt that building costs will increase because of these regulations, however, it is our job to convince the public that the extra expense is well worth the investment to provide the necessary protection. Other areas have experienced success in getting these regulations adopted provided the general public participated in the planning process. This can be done through a series of public hearings in which the public is encouraged to participate in the planning effort. Building materials and architectural designs should be studied to determine which

types are suited for our area to provde the maximum protection from an earthquake. This is expecially needed in all public buildings, hospitals, schools, fire stations, emergency vehicles, storage facilities, and utilities. A map showing which areas sustained the most, and type of, damages in the Charleston area from the 1886 earthquake would be most useful in any land management plan for the Charleston area. The map should also include all known fault locations.

3) All utilities should prepare a vulnerability analysis of their facilities to determine the potential damage that could occur. We can expect from a major earthquake, broken water mains that would hinder fire fighting capabilities, disrupted telephone communications would prevent the coordination of rescue and relief efforts, and disrupted sanitary sewer facilities could cause a major health problem if left unattended for a period of time.

   It is suggested that outside assistance be used in making this analysis, expecially form California and Alaska where they have had actual experience in dealing with a disaster.

4) All major transportation arteries and bridges need to be analyzed for survivability in case of an earthquake. This is especially critical in the coastal areas where one destroyed bridge could isolate a large segment of our population and prevent any effective relief effort from taking place for some time.

5) A structural inventory of existing buildings, including emergency facilities, should be undertaken by a team of experts to determine what degree of damage would occur if we have a major earthquake. A schedule of inspections should be implemented with the most critical structures undertaken first. Recommendations for building improvements should also be included in any undertaking.

SHORT-RANGE GOALS CONCERNING EARTHQUAKE HAZARD AWARENESS

In dealing with public apathy concerning earthquake hazard, immediate ways and means must be found to increase the public's hazard awareness, thus, making the long-range goals easier to obtain. The following are a few examples of ways that local community and State leaders can help in generating public awarness of the earthquake hazard:

1) States and or cities and counties can declare an "Earthquake Disaster Preparedness Week." This could be done in conjunction with press releases from the South Carolina Seismic Safety Consortium and national agencies.

   Public television could air programs on earthquake hazards and survival. Distribution of posters and pamphlets outlining the do's and dont's should we have an earthquake, would also be an effective means of getting public attention.

2) Workshops like this one always generate good press coverage and are an effective means of getting information to the public. The article that appeared in the Sunday edition of "The News and Courier," on April 24, 1983, was a major boost in our efforts to promote hazard awareness in this area.

3) Fire departments should be encouraged to stage earthquake drills either during National Fire Prevention Week or Earthquake Disaster Preparedness Week. These drills should take into account the disrupted or limited water supply that could hinder the fire fighting capabilities.

4) Public schools should be encouraged to have earthquake drills and prepare disaster plans. Plans should be distributed to the parents.

SUMMARY

The general public in the Southeastern United States presently believes that a major earthquake will not occur in this region. It is our responsibility as participants in this workshop to increase hazard awareness in this region, thus reducing the risk should a major earthquake occur.

HISTORIC SEISMICITY VERSUS TECTONIC HYPOTHESIS

by

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INTRODUCTION

Recently questions have been raised as to the validity of basing seismic design decisions on historic seismicity. It has been suggested that tectonic hypotheses should play the dominant role. It is perhaps trivial to place this discussion in a simple yes-no, mutually exclusive, historic versus tectonic framework. All thinking earth scientists would say that we have to use all the information we have available in order to arrive at the best answer. While this is obvious, there may be certain situations where a distinct choice lies in the type of information emphasized. I would like to discuss this choice in the context of the "Charleston" problem.

THE PROBLEM IN THE WEST AND THE EAST

In the Western United States, particularly California, the historic record and the theory of plate tectonics have combined to give us a fairly coherent picture of the nature of the earthquake hazard. The problem is not so much the "where" and "why" of earthquake occurrence but rather the "when". Plate tectonics allows us to predict fairly comfortably those places along the plate boundary that may have not seen large earthquakes in recent years but which should be considered likely locations for such events in the future. In the Eastern United States (east of the Rocky Mountains) the lower level of seismicity and monitoring and our lack of understanding with respect to causative mechanisms have placed us, for the most part, in a much more difficult position. Interpretation, primarily based on either historic seismicity or tectonic hypothesis alone, may result in dramatically opposed conclusions. For example, at Charleston, South Carolina, the occurrence of the 1886 event and the subsequent seismic activity could lead the analyst, relying on historic seismicity, to indicate this to be the highest risk area along the eastern seaboard. On the other hand, an analyst, relying on the decollement hypothesis, could indicate that the Charleston area represents a region of relieved strain energy making it possibly the least risky area along the entire eastern seaboard.

INTERDISCIPLINARY PROBLEMS

There is another aspect of the historic seismicity versus tectonic hypothesis debate that needs some discussion. A difference in opinion may often be a function of the discipline within which it is discussed and the specific goal that is sought. Earth scientists are interested in posing questions about the nature of the earth and in doing so advancing our basic knowledge. Engineers on the other hand, are primarily interested in solving problems. Intellectually stimulating tectonic hypotheses that provide interesting thought frameworks for interpreting millions of years of geologic history may not appear as useful as the actual record of earthquakes when one is designing structures to be safe over a lifetime of 40 to 50 years. For engineered facilities, however, that must consider much longer periods, such as nuclear waste repositories, the use of the historic record is constrained. Tectonic hypotheses begin to appear more attractive when one is trying the estimate hazard for periods an order of magnitude longer than the existing historic record.

THE CHOICES

In the present context of the "Charleston" problem; that is, arriving at sound engineering decisions for critical structures that have lifetimes of several tens of years, we are faced with two basic sources of information:

1. An historic record of earthquake occurrence that extends two to three hundred years, at least for large earthquakes.

2. An ever increasing array of tectonic hypotheses that, while intellectually stimulating, have not been proven or disproven.

It seems totally inappropriate to disregard the historic record in estimating seismic hazard. In many cases, the historic record is the only real evidence one has regarding earthquake potential in a region, the rest is supposition.

Summarizing the situation with respect to seismic hazard at Charleston and the rest of the eastern seaboard, I would recommend the following constraints.

1. Historic seismicity should be a necessary, but may not be a sufficient, element in our considerations.

2. Tectonic hypotheses alone are not as sufficient and may or may not be a necessary, ingredient in these considerations.

SEISMICITY, TECTONICS, AND SEISMIC HAZARD IN THE SOUTHEASTERN UNITED STATES

by

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DEFINITIONS

Seismic hazard - Any physical phenomenon (e.g., ground shaking, ground failure) associated with an earthquake which may produce adverse effects on human activities (cf. Seismic Risk - the probability that social or economic consequences of an earthquake will equal or exceed a specified value at a site, at several sites or in an area, during a specified exposure time). (Proposed Glossary of Terms for Seismic Risk Analysis, EERI Newsletter, vol. 15, no. 3, May 1981, pp. 55-61.)

Suspect terranes of orogenic belts are internally homogeneous geologic provinces, with features that contrast sharply with those of nearby provinces. They are recognized by contrasts in stratigraphy, structure, metamorphic and plutonic histories, faunas, mineral deposits, and paleomagnetic signatures. Their boundaries are sharp structural junctions marking discontinuities that cannot be explained by normal gradations in structural style, conventional facies changes or standard unconformities. Dimensions and form vary from those of small allochthonous rocks that have been moved a long distance from their original place of deposition by some tectonic process to major geologic provinces (Williams and Hatcher, Geology, 1982, p. 531). What is suspected is that the terranes formed far from their present surroundings, and were accreted to each other, to a continent, or both, by plate motions as an ocean closed.

HISTORICAL SEISMICITY AND TECTONICS AS INDICATORS OF SEISMIC HAZARD

Comparisons of tectonic and seismicity maps in the Southeastern United States show the maps to be very different. There is earthquake activity in trends that make both large and small angles with the regional tectonic and metamorphic fabrics. This results in the existence of both active and inactive portions within each of the various geologic provinces. Additionally, comparisons of historical (pre-network) and recent (post-network) seismicity maps indicate that regionally the seismicity tends to be spatially stationary and, to a lesser degree, is temporally stationary as well. Examples of seismic zones that are both spatially and temporally stationary include New Madrid, Missouri, and Charleston, South Carolina. Examples of zones that are either spatially or temporally nonstationary, or both, include Anna, Ohio (currently inactive) and northern Kentucky (currently active). The change from the "active" 19th century, with the Charleston, SC and Giles County, Virginia earthquakes and their aftershock sequences, to the "inactive" 20th century, with no comparable sequences, illustrates that the Southeast can be nonstationary in time.

The above observations suggest that there is some type of spatial selectivity in the accumulation and release of strain energy in the Southeast, at least for time intervals ranging from decades to centuries. Results developed during the past several years from regional geologic syntheses, seismic network monitoring, and reflection seismic profiling are beginning to shed light on the nature of that selectivity. Some results relevant to the specification of earthquake hazard are:

1) Suspect terranes

Williams and Hatcher have recently proposed a model of the Appalachian orogen as a mosaic of suspect terranes (Geology, 1982, pp. 530-536). Suspect terranes under other names have been inferred for parts of the Appalachians for over a decade (for example, Brown, 1970, in Fisher and others, eds., Studies of Appalachian Geology: Central and Southern; see review in Bollinger and Wheeler, USGS Open-File Report 82-585, 1982, pp. 20-21). Implicit in the concept of suspect terranes are compositional, structural and perhaps seismological differences between individual terranes. Thus, the individual terranes are natural candidates for zones that might be assumed seismically homogeneous for seismic hazard zoning. For example, the Charleston area lies in the suggested

Brunswick suspect terrane (BST); other seismically active areas in the Southeast lie in other terranes. We interpret the historical and recent seismicity in the Southeastern United States to exhibit a better spatial association with the inferred suspect terranes than with the classical geologic/topographic provinces. The association with terranes is admittedly speculative now, but it will become testable as additional, accurate seismological data are acquired and refinements/revisions of the terrane boundaries are developed.

2) Targets of opportunity

The seismicity in the Southeast could be due primarily to reactivation of a variety of preexisting structures by the contemporary stress regime. Those structures could, in turn, differ between the ancient craton and the various suspect terranes. Examples of such structures and their associated tectonic environments are:

Giles County, Virginia - The modern seismicity here has been mapped as a steeply dipping tabular zone occurring below the basal detachment (depths 5 to 25 km), within the cratonic basement, most probably on a compressionally-reactivated normal fault that formed when the lapetus Ocean opened, in late Precambrian or Cambrian time.

Central Virginia - This spatially diffuse seismicity appears to be primarily within the detached rocks (depths 10 km or less), above the basement, and on both nearly horizontal and steeply-dipping faults that probably formed during late Paleozoic compression.

Charleston, South Carolina, area - The seismicity defines several clusters with hypocentral depths from near-surface to some 18 km. Both a nearly horizontal detachment source as well as steeply-dipping faults have been proposed as causal. A detachment would probably have formed during Paleozoic compression, and a steeply-dipping fault during Mesozoic extension.

Mississippi Embayment - The seismicity here occurs in tabular zones within a rift in southeastern Missouri-northeastern Arkansas on compressionally-reactivated faults. The probable formation of those faults was during intracontinental rifting that developed at about the time of the opening of the lapetus Ocean.

3) Recurrence times

Long recurrence times appear appropriate for the area. Nuttli (USGS Open-File Report 81-437, 1981, pp. 111-123) used the South Carolina historical seismicity data (Tarr, USGS Prof. Paper 1028, 1977, pp. 43-58), with the 1886 event and its aftershocks deleted, to develop a log N versus M relationship that predicted (by extrapolation) a Charleston-size shock with a recurrence interval of 1000 years.

4) Aftershock sequence of the 1886 earthquake

New results, presented at the May 23-26, 1983, meeting in Charleston, SC, by L. Seeber and by P. Talwani, have convinced us that the aftershock sequence for the 1886 shock was most likely over by the turn of the century, or soon thereafter. In USGS Professional Paper 1313 (1983), one of us (GAB) had previously interpreted the temporal characteristics of the post-1886 seismicity as suggesting that the aftershock process was probably not over.

SUMMARY OF RECOMMENDATIONS

The preceding discussion suggests interrelationships between tectonics and seismicity in the evaluation of seismic hazard in the southeast. What is needed for specification of the Charleston source appears to be the following: (1) development of a better description of its host Brunswick suspect terrane (BST) and the nature of the coupling of that terrane with its neighbors; (2) incorporation of existing geological and geophysical data to develop crustal geological and velocity models with a geologically reasonable degree of vertical and horizontal heterogeneity for the BST in South Carolina; (3) development of improved relative hypocenter locations and focal mechanisms and of waveforms calculated from crustal models with imbedded source models; (4) specification of the uncertainties in the seismological results that arise from both analytical and geological variability and uncertainty; and (5) extensive and effective integration of geology and geophysics.

STRATEGIES FOR THE MITIGATION OF UNCERTAIN HAZARD FROM POTENTIALLY LARGE EARTHQUAKES

by

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INTRODUCTION

Several strategies are available to mitigate earthquake hazard when future large earthquakes are considered possible in a region, but their locations and times of occurrence are unknown. This is currently the case in the Eastern United States. The choice of a proper strategy requires balancing the advantages and disadvantages of each in order to achieve the maximum public safety for the lowest cost to society. Four strategies which are available can be described as follows:

Worst Earthquake. This strategy requires the design of all critical facilities for the worst earthquake hypothesized. In the Eastern United States this would entail designing facilities for a magnitude 7 shock assumed to occur in the near-field. The advantage of this strategy is conservatism; the disadvantage is extremely high cost to society, which ultimately pays for such conservatism.

Waiting For Scientific Advances. This strategy involves requiring no immediate seismic design changes to existing or planned facilities, and waiting until the causes (and presumably the possible locations) of future large earthquakes are understood scientifically. When this is achieved, facilities can be identified which are threatened, and seismic retrofit can be required. The advantage is that assets are only spent to upgrade facilities at risk. The disadvantage is that a large earthquake may occur before significant scientific advances have been achieved, resulting in disastrous consequences and large social costs from the affected facilities. The adoption of this strategy requires that the risk of this occurrence is acceptably low.

Identification of Likely Candidates. Under this strategy, the range of scientific opinion on earthquake occurrences is used to calculate the seismic hazard at facilities. Those facilities which appear particularly hazardous are upgraded; those which do not are deemed to have an acceptably low risk and are left unchanged. The advantage is that assets to upgrade facilities are spent only at locations where thev are expected to do the most good. The disadvantage is that, at sites perceived as hazardous, the effect of the "correct" hypothesis on earthquake occurrences may be diluted by alternatives, so that insufficient upgrading of seismic capacity is achieved and costly failures result if a large earthquake occurs. Also, if a currently-unpopular hypothesis on earthquake causes is later embraced by the scientific community, the retrofit of facilities originally deemed safe may be required. The net effect might be close to the cost for the "Worst Earthquake" strategy. However, if immediate seismic upgrading action for facilities is deemed necessary (because, for example, the prospects for near-term major scientific break-throughs are unlikely), this strategy is probably optimum.

Reliance on Precursory Seismicity. In this strategy, low and moderate seismicity (both activity and size) is relied upon to indicate locations of future large earthquakes. While the confidence in precursory phenomena need not be total, it needs to be sufficiently high that the risk of a large earthquake occurring near a critical facility without precursors needs to be acceptably low. The advantage of this strategy is that the cost of seismic safety is incurred at facilities where it is most beneficial. The disadvantage is that large earthquakes which occur without precursors may do significant damage to unprepared facilities. There are major benefits in terms of reduced costs associated with this strategy, either by itself or in combination with one of the other strategies, so that further examination of the temporal behavior of seismicity and seismic hazard is worthwhile.

NON-STATIONARY SEISMICITY AND SEISMIC HAZARD

The Chinese earthquake catalog contains a record of events over a period of some 2700 years and allows the evaluation of probabilistic seismic hazard analysis procedures. This catalog is particularly appropriate because it shows non-stationarity of activity (see Figure 1) and contains large events which purportedly occurred in previously aseismic areas.

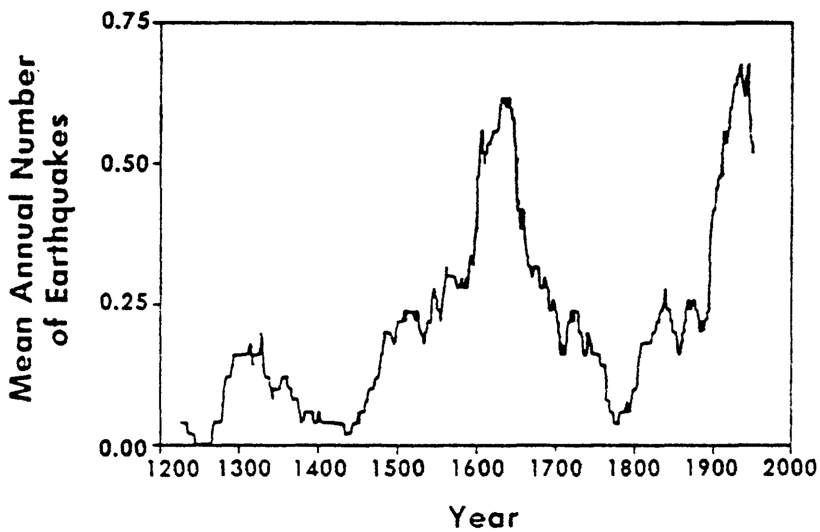

Figure 1.--Seismicity Variations in North China, 12-00-1950 (after McGuire and Barhnard, 1981)

To test probabilistic procedures for determining seismic hazard using the Chinese data, a method was devised which is described in detail in McGuire and Barnhard (1981). Briefly, the catalog was divided into 50- and 100-year segments, standard seismic hazard analysis assumptions (stationary, independent events occurring as a Poisson process) were made, and data in these segments were used to calculate probabilities of damaging shaking in 62 cities in north China during the 50 years following each time segment. The process was repeated for eleven time segments. Calculated probabilities were compared to the actual fraction of cities which experienced damaging shaking.

Figure 2 summarizes these results by showing calculated probabilities of damaging shaking versus observed fractions of cities experiencing damaging shaking, for corresponding 50-year time intervals. A perfectly-accurate hazard analysis would give results on the diagonal line. The open triangles result from a 50-year segment of seismicity used to predict hazard for the succeeding 50 years; these results are generally accurate and conservative.

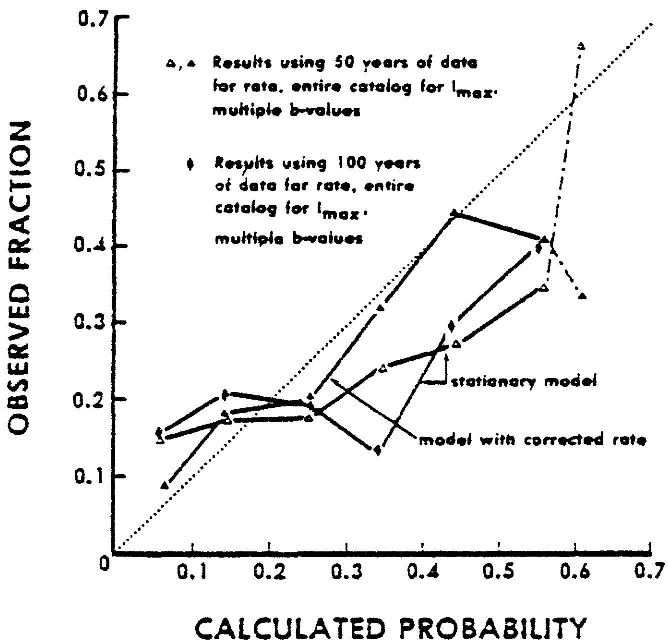

Figure 2.--Observed fraction versus calculated probability of damaging shaking at 62 cities in North China (after McGuire and Barhnard, 1981)

By contrast, the solid diamonds indicate a 100-year segment of seismicity used to predict a 50-year hazard. These results are less accurate and lead to the conclusion that the most recent past is the more accurate indicator of hazard in the near future. The solid triangles indicate results obtained by correcting the open triangles to use the actual rate of seismicity experienced in each seismogenic zone during the prediction interval; these results are highly accurate and justify the assumptions used in the hazard analysis.

The reason that only 50 years of data are sufficient for seismic hazard analysis is that large shocks, as a rule, do not occur as complete surprises; they are preceded by smaller events in the same locale. The 1920 magnitude 8.5 earthquake in Ningsia is often cited as being a "surprise", occurring in an area which was apparently aseismic for the previous 280 years. This must be considered in context, however; the Chinese catalog cannot be considered complete for magnitudes less than 6 or 6.5, so it can hardly be said with certainty that the area was aseismic. Additionally, a magnitude 6 shock occurred 68 years prior to the 1920 event, 120 km away, so that the general region, if not the exact epicentral area, would have to be considered tectonically active. Finally, the analysis conducted with the entire Chinese catalog indicates that events such as the 1920 shock are the extreme exception, rather than the rule.

EXPERIENCE IN THE EASTERN UNITED STATES

Available data indicate that the strongest earthquakes in the Eastern United States do not occur as complete surprises. Historical research of South Carolina, prior to the September 1, 1886, earthquake (Bollinger and Visvanathan, 1977; Reagor et al., 1980; Visvanathan, 1980) indicates that at least twelve small shocks strong enough to be felt occurred in the Charleston area in the 190 years prior to the large earthquake, and seven of these occurred in the period 1860-1886. Additionally, five MMI = V events occurred in the area in the 87 years preceding 1886, with two of these in the six preceding years. Thus, it cannot be said that the Charleston area was aseismic prior to 1886. Bollinger and Visvanathan (1977) make the point that the seismicity of South Carolina prior to 1886 does not appear anomalously high as compared to neighboring areas; this illustrates that not all low-level seismicity leads to major earthquakes.

Prior to the Cape Ann, Massachusetts, earthquake of 1755 (MMI = VIII, estimated magnitude of 5.8) there are historical accounts (Chiburis, 1981) of seven independent events with MMI $\geq$ IV in the Cape Ann area. One of these occurred in 1727 and was followed by numerous aftershocks. Again the Cape Ann earthquake cannot be considered a surprise.

There are, of course, apparent counter-examples. The July 1980 Kentucky earthquake (magnitude 5.2) and the January 1982 New Brunswick earthquake (magnitude 5.7) are illustrations of recent events which were unexpected. The point of this article is not to argue that a procedure now exists for identifying seismicity precursors to large shocks; rather it is to suggest that, if such a procedure can be devised, it will lead to significant savings in seismic hazard mitigation. The occurrence of seismicity precursors is logical and consistent with the notion that crustal faults are necessary but not sufficient conditions for earthquake occurrences: crustal stresses of adequate size, oriented in the proper direction, are also required. In the Eastern United States these crustal stresses increase slowly with time and must increase over a region to generate a large earthquake. The varying ability of faults in that region to resist stress implies that small shocks on weaker faults will act to relieve stress and, perhaps, concentrate it, before the large shock occurs.

BENEFITS OF RELIANCE ON SEISMICITY PRECURSORS

A strategy to use seismicity precursors to identify facilities requiring seismic retrofit can easily be illustrated. For the purposes of investigating the potential benefits, let us say that a facility will be shut down and retrofit for a high seismic design if two earthquakes with $m_b > 4.5$ occur within a 20 year period closer than 100 km (this distance implies an MM intensity > VII at the facility during a major, Charleston-size earthquake). Not all earthquakes with mb > 4.5 will lead to bigger shocks; in fact, the large majority of them will not, but the strategy assumes that we cannot identify the precursory small events from the others. From historical seismicity we observe that events with mb $>$ 4.5 occur about every five years on the eastern seaboard, so that the probability of occurrence per year is 0.2. Let us assume that, for the average site on the 2000 km-long eastern seaboard, a randomly-located earthquake will occur within 100 km of our facility 10 percent of the time.

The probability of two or more $m_b > 4.5$ earthquakes occurring within 100km of a site can be calculated from the Poisson distribution. The annual rate of occurrence within 100 km is 0.02 (the rate of occurrence of the event, times the probability it is close to the facility). For a time period t the probability of n events is

$$P(n) = \frac{(\upsilon t)^n e^{\upsilon t}}{n!}$$

For t = 20 years, P (0 events) is 0.67 and P (1 event) is 0.26, so the probability of seismicity meeting the precursory criterion is
1 - 0.67 - 0.26 = 0.07.

Let us say further that the cost of upgrading the facility's seismic design is \$20 million plus the costs (estimated at \$1 million per day) of shutdown to make repairs. The following two choices are available to the owners: (A) The facility can be upgraded immediately, in which case it is sufficiently safe to operate it during the 5 months necessary for design and analysis. Following this, a shutdown of one month is required for installation of retrofit equipment. The total cost of this option is \$50 million (\$20 million for repairs and \$30 million for 30 days of shutdown). (B) A second option is to wait to retrofit until precursors occur, using the above criterion to define precursors. If the precursory criterion is met, the facility will be shut down immediately until design, analysis and installation of retrofit equipment is complete. The cost associated with this outcome is \$200 million (\$20 million for repairs and \$180 million for 6 months of shutdown).

The most advantageous option can be determined with a decision tree. Figure 3 shows that an immediate decision to retrofit implies a cost of \$50 million. No retrofit means that the occurrence or non-occurrence of a precursor will

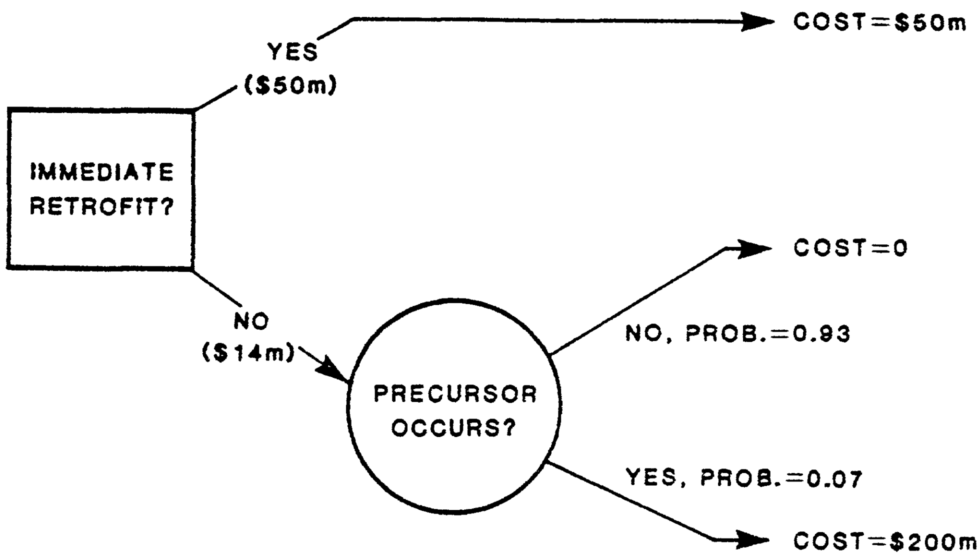

Figure 3.--Decision tree for "Waiting-for-Seismicity-Precursors" strategy.

there is not absolute confidence in precursory phenomena, the probability of a "surprise" event of a large size must be sufficiently low that it constitutes an acceptable risk. The potential benefits in reduction of seismic hazard mitigation cost suggest that close examination of precursory phenomena is appropriate. Note that the precursors necessar.v for a design strategy are different from those necessary for earthquake prediction: we can accept a high probability of false alarms from necessary-but-not-sufficient precursors, and still achieve large benefits in the costs of mitigating seismic hazards.

determine the cost. With probability 0.07 the cost of $200 million will be incurred; with probability 0.93 it will not. The expected cost for the no-immediate-retrofit decision is $14 million (the cost given the precursor, times the probability of the precursor). Unless the owner is extremely risk-adverse, the choice to await a precursor is optimal, for the example cited. Other examples can be analysed just as easily.

CONCLUSIONS

While the illustration presented here is cursory, it indicates that substantial cost savings to society may be achieved if we can account for expected time variations in seismicity and use them to define an optimum strategy for hazard mitigation. Ultimately the decision as to whether there is sufficient confidence in precursory seismicity to adopt such a strategy must be made as a consensus by scientists familiar with the evidence. If

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USE OF SEISMICITY AND TECTONIC FRAMEWORK TO DEFINE THE SEISMIC HAZARD IN THE REGION ENCOMPASSING CHARLESTON, SOUTH CAROLINA

by

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INTRODUCTION

Assessment of the seismic hazard of a site must take into consideration the size of the largest earthquakes expected in the region, distance from location of their source area, frequency of potentially damaging earthquakes and local ground conditions. In a region such as the Southeastern United States, where a large damaging earthquake like that at Charleston, South Carolina, is known to have occurred, the most critical factor for research becomes that of defining potential source zones. Without any defined source zone and reasonable cause for seismic activity, a large damaging earthquake might be expected to be generated anywhere within the region. This may lead to uniform, but rather expensive engineering design restrictions for large structures built anywhere in the region. Any general subdivision of the region into areas of greater and lesser seismic hazard ultimately rests on the concept of definable source zones. Statistical approaches using past seismicity, such as probabilistic methods, incorporate guesses as to the source zones and therefore have severe limitations and are scientifically unsatisfactory.

The problem is how to define and understand the source (seismogenic) zones in order to produce a seismotectonic or earthquake zonation map to show the regional variation in the seismic hazard. Despite the lack of demonstrable faulting associated with the 1886 Charleston earthquake, enough data on the region is now available to indicate the probable cause and source zone. The purpose of this paper is to summarize the data on the seismicity and tectonic framework of the region, to show the probable source zones of the Charleston seismicity and why it is unlikely that a large earthquake would occur just anywhere.

PATTERN OF SEISMICITY

The patterns of historical seismicity (Hadley and Devine, 1977; Bollinger and Visvanathan, 1977) and recent instrumentally recorded earthquakes (Tarr, 1977; Bollinger and Mathena, 1982) in the Southeastern United States are very similar and the persistent zone of recent activity to the northwest of Charleston may be associated with the source of the 1886 earthquake (Tarr, 1977) (Fig. 1). No significant change is discernable in source zones in the last 230 years in the Southeastern United States This consistency of pattern through time is also found in the Northeastern United States

The pattern is one of clusters of activity in South Carolina and central Virginia, a diffuse northeast-trending cluster along the axis of the Appalachian Mountains from western Alabama to northern Virginia and the absence of significant activity in eastern North Carolina and southern Georgia to Florida (Fig. 1).

The cluster of activity in South Carolina has a northwest-alignment passing through Charleston, from both historical and recent activity.' This was first noted by Hobbs in 1907 and by others since then. The effects of several earthquakes as shown by intensity distribution also show this northwest trend (Bollinger and Visranathan, 1977, Tarr, 1977, and Bagwell, 1981) and a well defined focal mechanism of an earthquake near Charleston suggests reverse faulting along a near vertical plane striking N42,W; the trace of this plane at the surface is along the Ashley River (Tarr, 1977).

TECTONIC FRAMEWORK

The exposed deposits in the Southeastern United States span Precambrian to Holocene time and reveal a great many tectonic and structural features. A profound break in the tectonic history of the region occurred during the Mesozoic when the North Atlantic basin began to open. It is the Mesozoic and younger features that should be expected to show relations with seismicity.

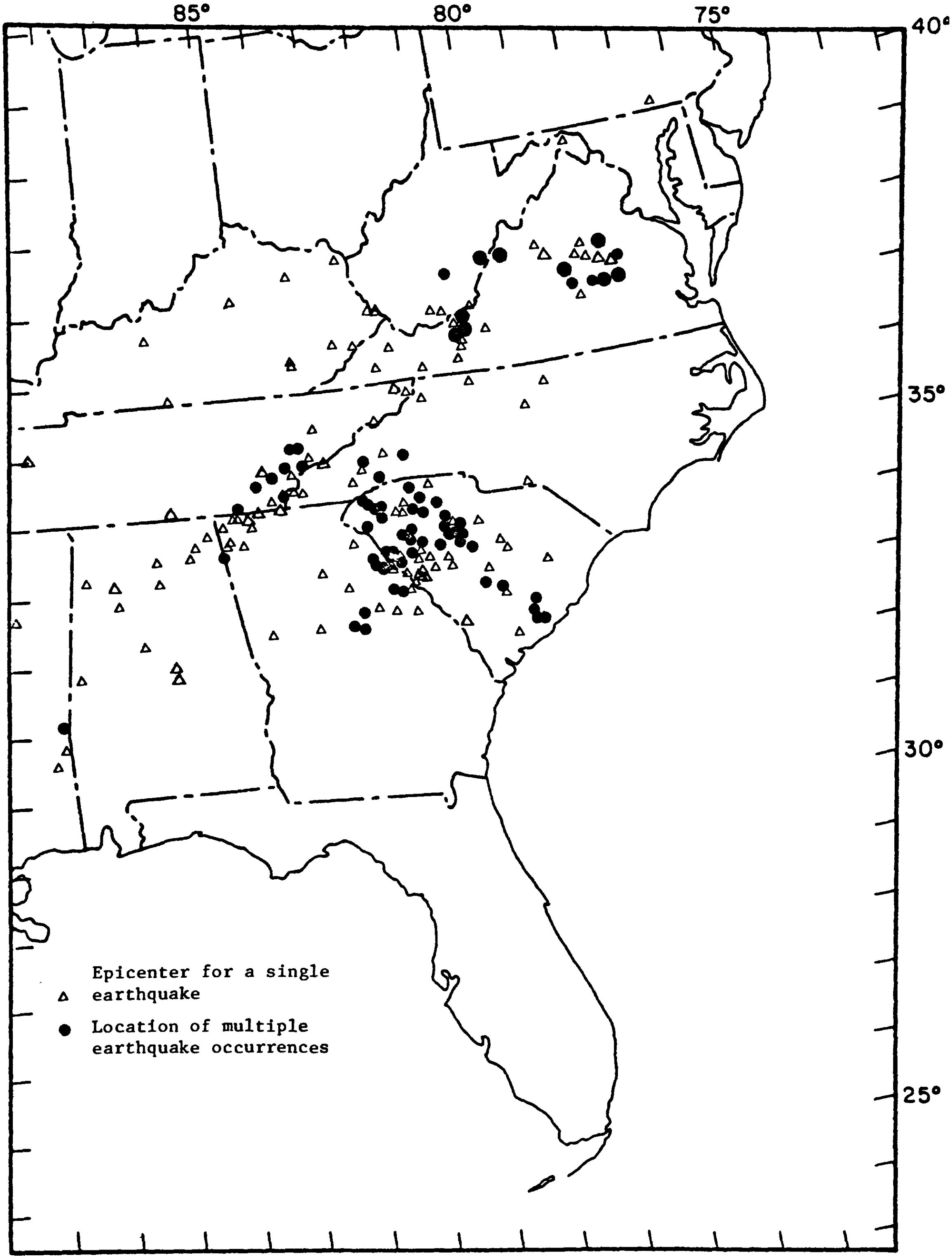

Figure 1. Earthquake Epicenters During the Period July 1977 - June, 1982 (Bollinger and Mathena, 1982).

The older features are only significant to the degree they may have been reactivated in post-Paleozoic time.

The region consists mainly of the Paleozoic and Precambrian rocks of the Appalachian orogenic belt and the Cretaceous and Tertiary rocks of the Atlantic and Gulf Coastal Plains (Fig. 2). Grabens of Triassic and Jurassic rock lie scattered in both the exposed southeastern part of the Appalachian orogenic belt and beneath the Coastal Plain. The Coastal Plain deposits form an apron at the edge of the continent and thicken seaward. This apron of sediments is not uniform but has been warped into a series of arches and embayments that have a northwest trending axis. These are well displayed by the sinuosity of the Cretaceous-Tertiary contact (Fig. 2). Offshore, a series of northwesttrending fracture zones cuts the ocean basins (Klitgord and Behrendt, 1979) (two of which are shown on Fig. 2). Inland a series of pre-Cretaceous Mesozoic basic dikes lies beneath and northwest of the Coastal Plain. The dikes trend northwest across Georgia and most of South Carolina and north across North Carolina.

MESOZOIC AND YOUNGER MOVEMENTS

A variety of vertical movements have effected the region since the Paleozoic northeast-trending grabens began to form on the southeast flank of the Appalachian orogenic belt when the rifting of the North Atlantic basin began during the Triassic. By mid-Jurassic the edge of the continent began to sag down (Grow, 1981). As this occurred the northeast-trending central part of the Appalachians rose and waseroded to provide sediments for the Coastal Plain deposits that built out over the sagging edge. This movement may have been at its maximum during the Late Cretaceous, but continued into the Tertiary.

Locally, slight downwarps and arches developed transverse to the Coastal Plain. The downwarps, refered to as embayments, were active during sedimentation and the stratigraphic layers thicken across them. The Salisbury and Southeast Georgia embayments are the major ones on the Atlantic Coastal Plain. Geomorphic studies indicate that the Appalachian core continued to rise during the Tertiary and geodetic measurements suggest it is still rising. Embayments continued to subside, as shown by the Lower Tertiary

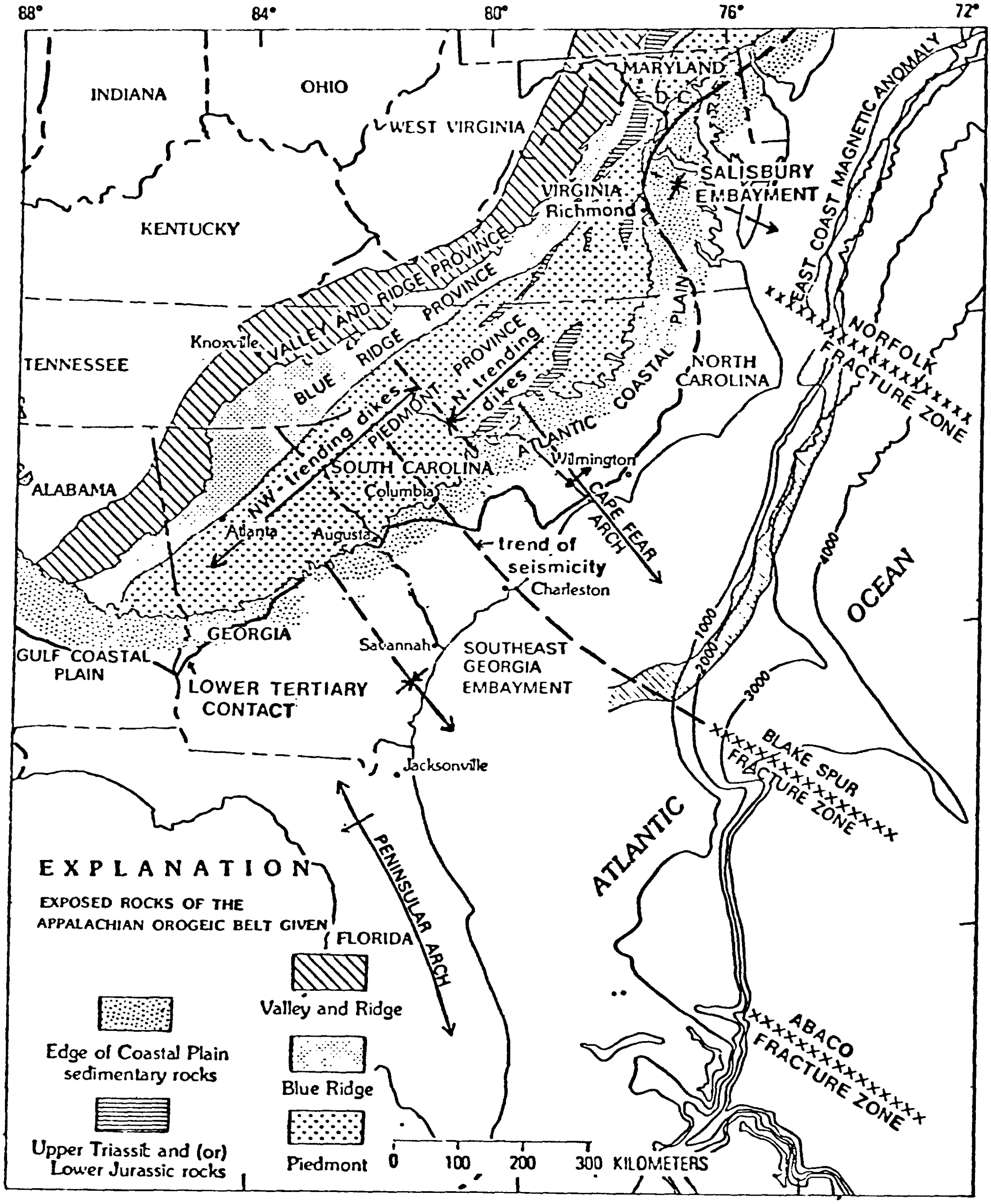

Figure 2.--Map of the Southeastern United States showing selected geologic features (compiled from King and Beikman, 1974; Cohee, 1961; Tarr, 1977; Rankin, 1977; and Klitgord and Benhendt, 1979) (from Barosh, 1981).

deposits. Upper Tertiary, Pliocene deposits are only found just offshore, along the axis of the Southeast Georgia embayment, due to direct or indirect effects of subsidence. The inner edge of the Coastal Plain is now above sea level, but warped shorelines indicate relative post-Pleistocene subsidence over the Southeast Georgia embayment (Winkler and Howard, 1977) (Fig. 3) and the expansion of the lower Chesapeake Bay over the Salisbury embayment may be due to subsidence there.

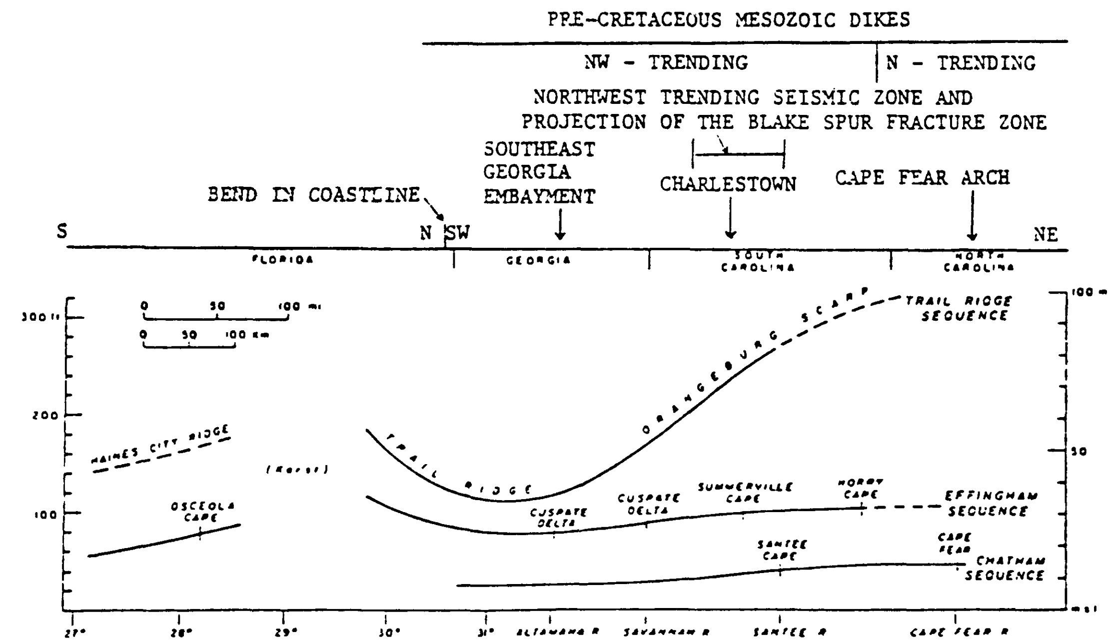

Figure 3.--Diagram showing tentative curves of shoreline warping along the south Atlantic coast (From Winkler and Howard, 1977) and their position relative to other geologic features (compiled from King and Beikman, 1974; and Cohee, 1961). The curves represent maximum height of transgression inferred for each shoreline sequence. Dashed lines indicate considerable uncertainty about sea levels. Vertical scale is altitute above present mean sea level (from Barosh, 1981).

Thus relative movements, rise of the Appalachian core and subsidence of embayments that were active during the Cretaceous and continued into the Tertiary are indicated to be still occuring today.

RELATIONSHIP OF SEISMICITY TO TECTONIC FEATURES

The general distribution of seismicity (Fig. 1) shows a correspondence with the latest vertical movements known in the region. The northeast-trending zone of activity alone the Appalachians Mountains is coincident with the rising core and the clusters of activity in central Virgina and in South Carolina lie at the innner edge of the embayments. The southwest Georgia embayment, indicated to have stopped subsiding, is essentially aseismic as are the Cape Fear and Peninsula arches.

The activity associated with the Southeast Georgia embayment lies not only at the inner edge of the embayment, but also extends along its northeast flank toward Charleston. This northwest-trending extension is aligned with the offshore Blake Spur fracture zone. A shoreward extension of this fracture may control both the flank of the embayment and the northwest-trending seismic zone.

CAUSES OF SEISMICITY

The seismicity in the Southeastern United States appears to be caused by adjustments on shallow local structures due to vertical movements brought about by continued opening of the North Atlantic basin. The main activity seems related to the relative subsidence at the inner edge of embayments on the Coastal Plain. This is the case on all the embayments in the Eastern United States (Barosh, 1981). The embayments here, and elsewhere, overlie older grabens that have apparently played a significant role in controlling their location. The small northeast-trending Miocene graben, the Gulf trough, across the Georgia portion of the Southeast Georgia embayment (Miller, 1982) probably represents a slight reactivation of a much larger Triassic-Jurassic graben that underlies the embayment. The northwest-trending embayments on the East Coast may also be controlled by the northwest-trending fracture zones shown offshore by Klitgord and Behrendt (1979). Extensions of the Abaco and

Blake Spur fracture zones would bound the Southeast Georgia embayment (Fig. 2). The East Coast magnetic anomaly is offset opposite the Salisbury embayment by the Norfolk fracture zone that may have helped control the location of that embayment (Fig. 2). The concentration of northwest-trending pre-Cretaceous Mesozoic dikes across South Carolina (Popenoe and Zietz, 1977) could be related to early movement on the Blake Spur fracture zones.

The local control of the 1886 Charleston earthquake may well be due to movement on a northwest-trending normal fault along the Ashley River as suggested by Pradeep Talwani (oral communitcation, 1982). This structure is also indicated by the northwest elongation of effects (isoseismals) along the river (Bagwell, 1981) and a fault plane solution (Tarr, 1977) from recent earthquakes. This active trend is in agreement with findings in the Northeastern United States where the northwest-trending high-angle faults, in places associated with north-trending ones, are always found to be the youngest structures.

CONCLUSIONS AND RECOMMENDATIONS

Several conclusions can be drawn from this discussion:

1. Seismicity and tectonic features can be used together to determine reasonable causes and source zones in the region encompassing Charleston, S.C.; used separately, the results are unsatisfactory.

2. The general pattern of seismicity appears to have remained the same throughout the historical and recent record.

3. Mesozoic and younger tectonic features are the important ones to be conaidered; Paleozoic ones are only significant if reactivated in the Mesozoic.

4. The general seismicity appears caused by adjustments on shallow local structures due to vertical movements brought about by continued opening of the North Atlantic basin, the relative rise of the core of the Appalachian Mountains and subsidence at the heads of embayments.

5. Positive structures on the Coastal Plain are essentially aseismic.

6. The position of the embayments appears controlled by both underlying grabens and landward extensions of the fracture zones in the ocean basin.

7. The landward prolongation of the Blake Spur fracture zone coincides with a northwest-trending zone of seismicity across South Carolina.

8. Movement along an apparent northwest-trending normal fault that follows the Ashley River northwest of Charleston is the most likely source of the 1886 earthquake.

9. Tectonic features associated with the seismicity in the region around Charleston, S.C., are similar to those found in other seismically active areas in the Eastern United States.

10. Source areas responsible for the seismic hazard in the region should not change in position over the next few hundred years, although earthquakes larger than those recorded to date for some places within these source areas may be expected to occur.

Further research should place highest priority on continuing to improve the knowledge of earthquake locations and delineating recent tectonic movements across the region and on defining structure in the 1886 epicentral area. More studies with local seismic arrays could be done within the active areas and perhaps additional permanent stations added to the present network in the less active areas for more uniform coverage. Present and past vertical movements could be investigated by remote sensing, detailed geomorphic, Cretaceous and Tertiary stratigraphic, and geodetic studies. Within the epicentral area a very detailed geomorphic study should be made to look for landscape changes, gravity data collected to produce a complete Bouguer residual map of at least 1 milligal contour interval and an aeromagnetic survey conducted with a flight line spacing of 0.4 km or less. Also, some additional shallow drilling and stratigraphic work could better define the inferred Ashley River fault.

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A GLOBAL SEARCH OF CONTINENTAL MIDPLATE SEISMIC REGIONS FOR SPECIFIC CHARACTERISTICS BEARING ON THE 1886 CHARLESTON, SOUTH CAROLINA, EARTHQUAKE

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ABSTRACT

Properties of selected source regions of midplate earthquakes are examined in light of hypotheses on the characteristics of the source of the 1886 Charleston, South Carolina, earthquake. Data from the other midplate source regions suggest that the Charleston region is more likely to experience a strong earthquake in future decades than a random midplate site, but that strong Eastern United States earthquakes will also occur in the future at sites that have not been previously experienced strong earthquakes. Data from the other regions do not provide conclusive seismological or geological guidelines for identifying sources of future strong earthquakes in the absence of a historical record of strong earthquakes. In particular, most of the other strong midplate earthquakes are not clearly associated with prominent pre-existing faults. However, the relatively shallow focal depths of most midplate earthquakes and the fact that many of the midplate sources show a general correlation with regional geologic structure, even if they cannot be assigned to specific mapped faults, support the view that the sites of strong midplate earthquakes are determined by pre-existing geological structure. For several midplate earthquakes, the size of the aftershock zone is much larger than the size of the mainshock fault rupture; by implication, the aftershock zone of the 1886 Charleston earthquake may have been much larger than the causative fault of the earthquake.

INTRODUCTION

This paper is a review of studies of selected sources of "strong" (M = 5.5 or greater) earthquakes in continental midplate environments worldwide. The other source regions cannot be viewed as exact analogs of the Charleston source, but they may be similar in characteristics that influence the generation of strong earthquakes, and they provide empirical guidelines for evaluating the reasonableness of hypotheses proposed for the Charleston source or for other possible sources in the Eastern United States.

The properties of the earthquake source summarized here are: (1) year and magnitude of strong earthquakes, (2) depth of the source beneath the earth's surface, (3) the orientation and sense of slip on the faults producing large earthquakes in the source, (4) whether or not the earthquakes occur on mappable pre-existing faults, (5) whether or not the source has produced repeated strong earthquakes over a period of decades or centuries, (6) whether or not the source could have been identified on the basis of small earthquakes before the occurrence of the first known large earthquake, (7) notable characteristics of the aftershock sequence, and (8) differences between the source region and the 1886 Charleston source region that might weaken the drawing of an analogy between the two.

GENERAL COMMENTS ON PARAMETERS BEING REVIEWED

Magnitude: I will use the following abbreviations for magnitudes that have been assigned to the earthquakes being reviewed: mb (body wave magnitude computed from short period P-waves), ML (local magnitude), MS (surface-wave magnitude computed from 20-second surface waves), M (type of magnitude not stated, but probably equivalent to ML or MS). These distinctions are necessary because observational and theoretical studies have established that different types of magnitude will generally not have the same value for a given earthquake (Richter, 1958; Geller and Kanamori, 1977).

Focal depth: Recent studies (Meissner and Strehlau, 1982; Sibson, 1982; Chen and Molnar, 1983) provide evidence that earthquakes in midplate regions such as the Eastern United States may occur at greater depths (up to 25 km) than earthquakes in many sources of the Western United States such as the San Andreas fault (hypocenters shallower than 15 km). Sibson (1982) and Meissner and Strehlau (1982) hypothesize that the largest earthquake in any given seismic source may nucleate at the depth of the deepest small earthquakes in the source and propagate upwards from this depth. Under this hypothesis, the deeper the distribution of small earthquakes in a region, the deeper the large shocks and, therefore, the less likely that large shocks will have associated surface rupture and, in general, the less likely that near-surface geology will reflect conditions at the seismic source beneath. It is also possible that regional variations in the maximum focal depths of small earthquakes might provide a basis for zoning for large earthquakes in the Eastern United States (Sbar and Sykes, 1977).

Focal Mechanism: Worldwide, midplate earthquakes may originate as the result of reverse faulting, strike-slip faulting, or, less frequently, normal faulting (Richardson and others, 1979); the global data do not argue that one of these general types of faulting can be excluded "a priori" as a candidate for the cause of the 1886 earthquake. Specific faulting mechanisms that have been proposed for the 1886 earthquake and which therefore can be "tested" by searching elsewhere for analogues, are: (a) reverse faulting on a reactivated, formerly normal, fault (Wentworth and Mergner-Keefer, 1981), (b) reverse faulting on a nearly horizontal decollement (Behrendt and others, 1983), (c) normal faulting on a nearly horizontal decollement (Seeber and Armbruster, 1981), and (d) strike-slip faulting at depth beneath a zone of more shallow vertical-slip faults (Talwani, 1982).

Preexisting Faults: It has proven difficult to associate most Eastern United States earthquakes with major preexisting faults and, conversely, a number of mapped faults with Cenozoic offset do not have epicenters of earthquakes associated with them. It is possible that the rather low correlation between epicenters and mapped major faults in the Eastern United States is partly the result of the faults being present but unmapped (Wentworth and Mergner-Keefer, 1981) or the result of the fault's seismicity escaping detection by the regional seismographic network. In addition, evidence from more seismically active regions of the earth suggests that potentially dangerous faults may be quiescent for long periods between strong earthquakes, whereas minor seismicity may occur at many sources that are unlikely to produce major earthquakes (Allen and others, 1965). In the next section, the lack of an entry entitled "Preexisting Faults" means that the seismologically-oriented papers that I consulted did not provide strong evidence for or against the existence of a preexisting fault. I did not consult the general geological literature for evidence on pre-existing faults.

Repetition: Some midplate source regions with dimensions of tens of kilometers or less have produced more than one strong earthquake over periods spanning decades or centuries. Because elastic strain normally accumulates slowly in midplate regions, it is difficult to visualize how seismic slippage could recur on the same fault surface within which strain had been relaxed by an earthquake decades or centuries earlier. Possibly the later earthquakes in an extended sequence of strong shocks correspond to extension of fault rupture from the source of the earlier earthquakes into as yet unruptured, strained, medium.

Previous smaller earthquakes: The relative infrequency of strong earthquakes from any one source in the Eastern United States makes it very unlikely that all potential sources of strong earthquakes will have produced such an earthquake in the several centuries of our history (McGuire, 1977). At best, we can hope than many of these potential sources of strong earthquakes will reveal themselves by producing, prior to the next strong earthquake, small or moderate earthquakes whose characteristics, together with characteristics of the geology of the source regions, will indicate that these sources are capable of producing strong shocks.

Aftershocks: I will define a "normal" aftershock sequence to have two properties. First, the aftershocks in a "normal" sequence occur on, or very near to, the fault plane of the main shock, so that the distribution of aftershocks provides a slightly out-of-focus picture of the mainshock fault plane. This property is often assumed in the interpretation of aftershock sequences, and is based on the fact that the largest changes in elastic strain produced by an earthquake will occur within a distance of one fault length from the causative fault (e.g., Das and Scholz, 1981). However, this property is contradicted by some aftershock sequences, and it is possible that some aftershocks are triggered by the very small changes in strain that occur at distances of several fault lengths from the causative fault (Das and Scholz, 1981). Second, the frequency of aftershock occurrence in a "normal" sequence decays within a relatively short time (several years in the case of an earthquake of magnitude about 7, the magnitude of the 1886 Charleston earthquake) after which the source of the strong earthquake is not notably more active than it was prior to the occurrence of the strong earthquake. Some seismologists would argue that this property of "normal" aftershock sequences is in fact abnormal, but it serves as a standard with which to compare observations. The lack of an entry under "Aftershocks" for a particular earthquake means that available data do not resolve inconsistencies between the observed and "normal" aftershock sequences.

Differences: The regions considered in this review are similar to the Charleston region by virtue of being located away from the global belts of seismicity that are associated with active plate boundaries. The regions are, however, different in other ways from each other and from the Charleston region. One would hope that, among hypotheses proposed for Eastern United States earthquakes, the hypotheses most likely to be correct are those that are also consistent with observations from other midplate regions of the world. However, we run the risk that some of the other source regions may correspond to completely different geological processes than those at work in the Eastern United States. A number of differences will be evident from comparison of parameters discussed previously in this section; I will discuss under "Differences" other characteristics that differ between the Charleston region and the other midplate region.

SPECIFIC MIDPLATE SOURCE REGIONS

A) Baffin Island, Canada: A region on and offshore of the northeast coast of Baffin Island, with dimensions of several hundred kilometers, experienced strong earthquakes in 1933 (MS = 7.3) and 1963 (MS = 6.2) (Qamar, 1974; Sykes, 1978; Stein and others, 1979; Basham and Adams, this volume).

Depth: The 1933 earthquake is now thought to have had a focal depth of approximately 25 km, based on preliminary analysis of depth phases recorded at a number of seismographic stations (Stein, personal communication, 1983); the previous estimate of 65 km reported by Stein and others (1979) was based on one seismogram. The 1963 earthquake had a focal depth of about 7 km (Liu and Kanamori, 1980).

Focal Mechanism: The 1933 earthquake occurred beneath Baffin Bay as the result of reverse faulting (Stein and others, 1979). The 1963 earthquake occurred beneath the coastline of Baffin Island as the result of normal faulting (Stein and others, 1979); its focal mechanism is consistent with, but does not require, a shallowly dipping normal fault as the causative fault.

Previous Smaller Earthquakes: The epicentral regions of the 1933 and 1963 earthquakes were too remote from population centers and seismographic stations to test for prior small earthquake activity.

Aftershocks: The source region of the 1933 earthquake has continued to produce moderate-sized earthquakes at least into the mid-1970's. Since we do not know the frequencey of moderate-sized earthquakes for the decades prior to the 1933 earthquake, we cannot discriminate between the possibilities that the more recent shocks are long-delayed aftershocks to the 1933 earthquake or, conversely, that the recent activity represents the background level of activity in a persistent intraplate source.

Differences: The 1963 Baffin Island source is located on a continental margin with much higher relief than in the Charleston region. It is possible that such a normal faulting earthquake could occur in the Baffin Island region due to large variations in topography and crustal thickness (Bott and Dean, 1972) but would be unlikely to occur by this mechanism near Charleston. The Baffin Island region, in common with other Canadian sources to be discussed subsequently, was under a thick ice load in the late Pleistocene; stresses resulting from the removal of the load may be producing the present seismicity (Stein and others, 1979). The hypocenter of the 1933 earthquake was probably in oceanic upper mantle rather than deep continental crust (Reid and Falconer, 1982); the rheological properties of this upper mantle material, which influence the depth at which earthquakes occur, are probably much different than the continental crust at a depth of 25 km beneath Charleston (Chen and Molnar, 1983).

B) La Malbaie (Charlevoix) Zone, Quebec: A region extending approximately 70 km along the St. Lawrence River produced earthquakes of magnitude 6 and greater in 1663, 1791, 1860, 1870, and 1925 (Basham and others, 1979; Stevens, 1980, Leblanc, this volume). The largest shocks (1663 and 1925) had magnitudes of about 7.

Depth: Recent microearthquake activity in the source occurs above 25 km focal depth, with most activity concentrated between 7 km and 15 km (Anglin and Buchbinder, 1981; Leblanc, this volume). Dewey and Gordon (written communication, 1983) computed a focal depth of 9 km for the shock of 1925. Although this computed focal depth is estimated to only be precise to within 13 km at a 90 percent level of confidence, the new analysis rules out the focal depth of 60 km once assigned to this shock on the basis of its large felt area (Gutenberg and Richter, 1954).

Focal Mechanism: Most focal mechanisms determined for smaller earthquakes in the La Malbaie region have involved reverse faulting or oblique-slip faulting with a reverse component of slippage (Hasegawa and Wetmiller, 1980).

Preexisting Faults: Anglin and Buchbinder (1981) suggest that seismicity at La Malbaie is occurring as a consequence of reverse slippage on reactivated, originally normal, faults of the St. Lawrence paleo-rift system (Kumarapeli, 1978). The precise faults on which the earthquakes are occurring have not been identified.

Repetition: The La Malbaie source is an outstanding example of a well-circumscribed midplate source producing repeated strong earthquakes over a period of several centuries. The overall zone of microearthquakes in the source is about 70 km long. Most of the moderate and strong 20th century earthquakes from the source have occurred in a smaller region at the northeast end of the microearthquake zone (Stevens, 1980), but the pre-twentieth-century earthquakes are not well-enough located to determine if they also occurred at the northeast end of the microearthquake zone.

Differences: The La Malbaie source differs from the Charleston source in a number of characteristics and, for each characteristic, the differences are those that would usually be interpreted as implying a greater likelihood of a large earthquake at La Malbaie than at Charleston. Besides its historical tendency for repeated strong earthquakes, its location in a paleo-rift, and the length of the zone of small earthquakes, the La Malbaie source lies in a region of relatively high relief and aseismic deformation (Basham and others, 1979). In addition, the source is near a major meteor impact crater that may have changed the elastic properties of the earth's crust in some way that is favorable to the occurrence of large earthquakes (Anglin and Buchbinder, 1981; Leblanc, this volume)

C) Miramichi, New Brunswick: Central New Brunswick experienced a strong (mb = 5.7, MS = 5.2) earthquake in January, 1982 .

Depth: Choy and others (1983) estimate a focal depth of 9 (s.e. = 1.3 km) for the point of nucleation of the main shock, on the basis of a detailed analysis of the seismic waveform. Aftershocks were virtually all located above a focal depth of 7 km (Wetmiller and others, 1982).

Focal Mechanism: The earthquake had a predominantly reverse fault focal mechanism (Choy and others, 1983). Teleseismic waveforms are consistent with fault rupture propagating upwards from the point of nucleation (Choy and others, 1983).

Preexisting Fault: The earthquake did not occur on a previously mapped preexisting fault; I am not aware that retrospective analysis of the source region has turned up a good candidate for the causative fault. Choy and others (1983) suggest, however, that the steep dip of their inferred fault plane may point to the earthquake occurring as reverse slip on a preexisting, formerly normal, fault, rather than as a new fracture in previously intact rock.

Repetition and Previous Smaller Earthquakes: The source region of the Miramichi earthquake had not been specifically recognized as a potential site of strong earthquakes prior to 1982. In general, the broader region of northern New England and New Brunswick has not been characterized by compact, well-defined sources of persistent activity. Instead, sources of small and moderate earthquakes have been scattered widely over the region, and there has not been a strong tendency for moderate shocks to recur within tens of kilometers of a moderate earthquake from previous decades. Some of the other earthquakes of northern New England and New Brunswick, such as the Ossipee, New Hampshire, earthquakes of 1940, have had magnitudes similar to that of the 1982 New Brunswick earthquake .

Aftershocks: The small aftershocks to the 1982 earthquake define a volumnar source that cannot be fit with a single plane (Wetmiller and others, 1982). In June 1982, nearly half a year following the 1982 mainshock, there occurred a magnitude 4.6 (mb) earthquake located approximately six fault-lengths away from the source of the January 1982 mainshock. The two shocks are close enough together in space and time that the possibility of a causal relation must be considered.

D) Western Quebec Source Region (Western Quebec and adjacent parts of Ontario and New York): This source region covers an area of 500 km by 300 km. Earthquakes have occurred at many widely separated locations in the zone, rather than at a few discrete sources. The largest shocks of the instrumental era were the Timiskaming, Quebec, earthquake of 1935 (MS = 6.2) and the Cornwall, Ontario -- Massena, New York, earthquake of 1944 (MS = 5.8).

Depth: Well-determined focal-depths in the Western Quebec Zone range from near-surface to about 20 km (Horner and others, 1978; Yang and Aggarwal, 1981).

Focal Mechanism: Earthquakes in the Western Quebec Zone have predominantly reverse-fault focal mechanisms (Yang and Aggarwal, 1981).

Preexisting Faults: Association of seismicity with preexisting faults has been difficult to demonstrate. The two largest shocks whose epicenters are known from instrumental data, the 1935 and 1944 earthquakes, occurred in an area of post-Grenville faults associated with the Ottawa-Bonnachere Graben (Forsyth, 1981). Most of the smaller shocks, however, occur away from the zone of mapped, most recent, faulting (Forsyth, 1981). Yang and Aggarwal (1981) have suggested an association of seismicity with geologic lineaments in upstate New York.

Repetition and Previous Smaller Earthquakes: At the broad scale of 50 to 100 km, the Western Quebec Zone as defined by small and moderate earthquakes occurring after 1975 is generally similar to the zone as defined by moderate and strong earthquakes occurring prior to 1975 (Sykes, 1978). Shocks in the zone do not seem to have long-lasting aftershock sequences (see below), so the similarity of the two sets of data suggests an underlying geologic control to the boundaries of the zone, as has been proposed by Forsyth (1981). An exception to the broad scale similarity between the distribution of small earthquakes and large earthquakes occurs for the source of the 1935 Timiskaming earthquake. The 1935 epicenter is about 100 km away from the rest of the Western Quebec Zone.

Aftershocks: The areas within tens of kilometers of the strong earthquakes of 1935 and 1944 do not appear as conspicuous zones of seismicity in maps of recently occurring shocks (Dewey and Gordon, written communication, 1983); aftershock activity from these earthquakes seems to have diminished quite rapidly.

E) Mississippi Embayment: Some of the largest midplate earthquakes in the past two centuries occurred in the Mississippi Embayment near New Madrid, Missouri in 1811 and 1812. Three of these earthquakes had magnitudes (mb) greater than 7 (Nuttli, 1982).

Depth: Well-determined focal depths of small and moderate earthquakes in the zone vary from near-surface to about 20km (Herrmann, 1979).

Focal Mechanism: Focal mechanisms of small and moderate earthquakes in the zone are consistent with fault slippage under the effect of a compressive stress oriented approximately east-west. Earthquakes occurring in a major northeast striking zone of epicenters have focal mechanisms consistent with right-lateral faulting on northeast-striking planes; earthquakes occurring on a north-northwest zone of epicenters have mechanisms generally consistent with reverse faulting on north-northwest striking planes (Herrmann and Canas, 1978; O'Connell and others, 1982).

Preexisting Faults: The earthquakes occur in a pre-Late Cambrian rift system (Hildenbrand and others, 1982). Intensive studies have found evidence for Cenozoic deformation (Russ, 1982; Hamilton and Zoback, 1982).

Repetition: Although the Mississippi Embayment source has produced a number of strong shocks in historical time, the epicenters of these shocks, to the extent that they can be resolved, are consistent with each of the shocks occurring on a fault or source volume that had not been ruptured by one of the preceding historical strong earthquakes. Thus the isoseismals of the three largest earthquakes of the 1811 - 1812 sequence suggest that the epicenter of each of the later shocks was northeast of the preceding (Nuttli, 1982). The strong earthquakes of 1843 and 1895 occurred at the ends of the 1811-1812 earthquake zone (Nuttli, 1982). Considering periods of five centuries or more, it is possible that strong earthquakes have recurred on the same fault segment. Not withstanding that the average rate of deformation for the entire Cenozoic (.001 mm/yr., McKeown, 1982) would imply recurrence times on the order of a million year for a major earthquake on a given fault in the Mississippi Embayment, deformation in the last few thousand years has been much higher than the long-term average, and several observations are consistent with recurrence times of 600 years for the last two millenia (Russ, 1982).

Differences: The Mississippi Embayment source, although not completely understood, has a number of characteristics often found in significant seismic zones that have not yet been found in the Charleston region. The recent small and moderate earthquake activity is strongly concentrated in linear zones within the paleo-rift. The rift itself, as revealed by aeromagnetic data (Hildenbrand and others, 1982), has straight, well-defined boundaries with lengths of at least 200 km.

F) Great Britain and Fennoscandia: The largest known British earthquake had a magnitude of about 5.5 (Scott, 1977); the historical record of shocks of magnitude 5.5 or greater should be complete for the past thousand years (Gutenberg and Richter, 1954). The largest known Fennoscandian earthquakes, in a record thought to be complete for the past four hundred years (Husebye and others, 1978), had magnitudes of about 6.0.

Depth: Reliably-determined focal depths have ranged from near surface to about 25 km, with most occurring in the uppermost 15 km (e.g. Bungum and others, 1979; King, 1980; Slunga, 1979; Slunga, 1982)

Focal Mechanism: Reverse (e.g. King, 1980), strike-slip (e.g. Slunga, 1982), and normal (e.g. Bungum and others, 1979), faulting focal mechanisms have been determined for shocks in the region of Great Britain and Fennoscandia.

Previous Smaller Earthquakes: The most damaging historical earthquake beneath the landmass of the British Isles had a magnitude of 5.0-5.5 (Scott, 1977) and occurred in a region that had not previously experienced small earthquakes (Davison, 1924). Other moderate and strong shocks in Britain and Fennoscandia have tended to occur in regions of previous small earthquake activity. Small earthquakes occur over such a broad area of Britain and Fennoscandia, however, that knowledge of a tendency for strong shocks to occur in regions of small shocks is not very useful unless it becomes possible to discriminate between source regions of small shocks that are likely to produce strong shocks and source regions of small shocks that are not likely to produce strong shocks.

G) Ebingen, Swabian Alb, Germany (Figure 1): Earthquakes of magnitude (ML) 5.5 or greater have occurred in 1911 (ML = 6.1, MS = 5.5), 1943 (ML = 5.5, MS = 5.2), and 1979 (ML = 5.7, MS = 5.1) in a source with dimensions of about 10 km near Ebingen (Haessler and others, 1980).

Depth: Focal depths are from 5 to 10 km.

Focal Mechanism: All strong earthquakes had strike-slip focal mechanisms.

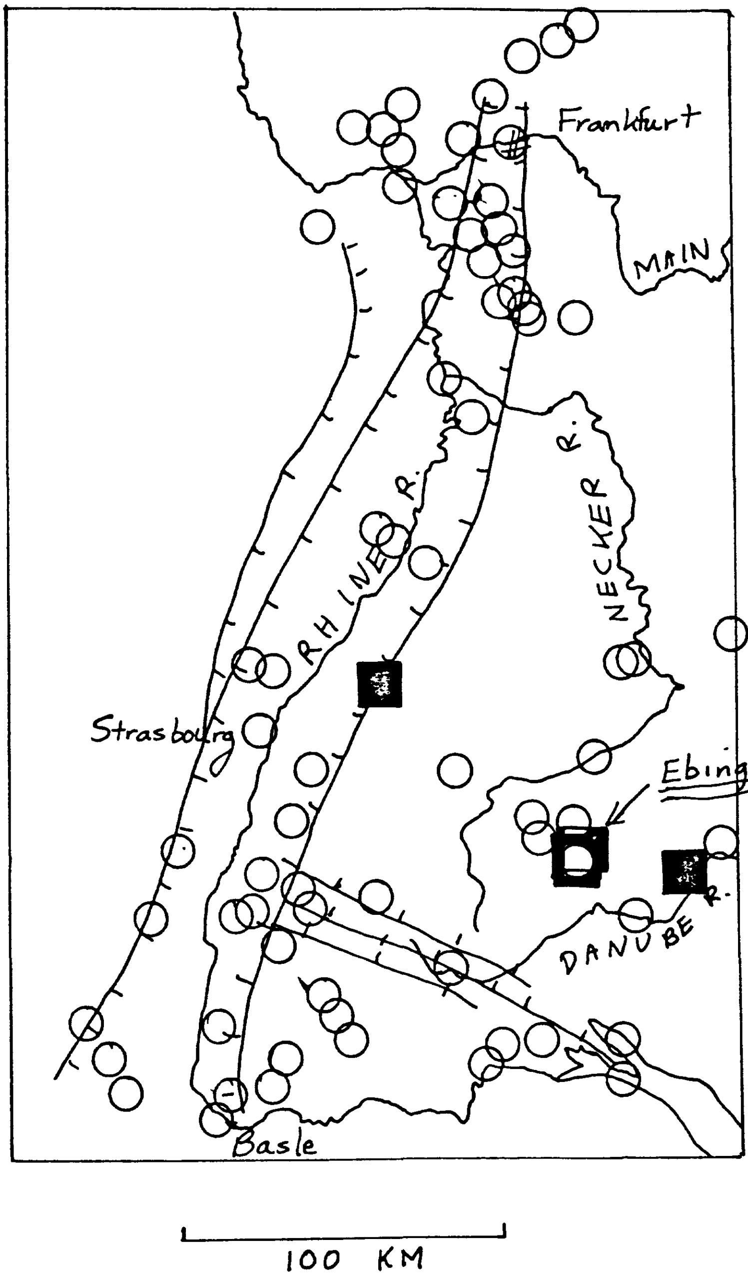

Figure 1.--Seismcity near the Ebingen source in southwestern Germany. Seismicity prior to 1906 is from Montessus de Ballore (1906) and each symbol represents a site where earthquakes were felt, rather than the epicenters of earthquakes. Montessus de Ballore's lowest class of felt activity is omitted. Symbols of post-1906 earthquakes are plotted at the epicenters. The open circles show pre 1906 seismicity; the filled squares show events having magnitudes of 5 or greater for the period 1907-1982.

Preexisting Faults: Schneider (1979) cites Carle (1955) as identifying a basement lineament passing through the Ebingen source, with a north-northeast strike that agrees with the strike of the faulting revealed by first-motion studies. Interestingly, the uppermost several kilometers of the earth's crust beneath the epicentral region is occupied by a shallow graben that strikes northwest. In the case of the Ebingen source, therefore, the most prominent faults identifiable at the surface are shallow-rooted faults that have a different strike and sense of displacement from those of the fault causing the earthquake.

Repetition: The 1911 earthquake was the first strong earthquake from the Ebingen source in the historical record. The 1943 and 1979 shocks are each inferred to have occurred several kilometers north of the preceding strong shock (Haessler and others, 1980). This would imply that the apparent repetition of strong shocks from the same localized source actually corresponds to an episodic propagation of rupture northward along the causative fault.

Previous smaller earthquakes: Towns in the epicentral region of the Ebingen source had experienced small earthquakes prior to the 1911 earthquake (Montessus de Ballore, 1906, Schneider, 1979). The epicenters of these shocks cannot be located with precision sufficient to determine if they occurred right at the Ebingen source. The region of the Swabian Alb was shaken in 1827 by a moderate shock that was centered about 25 km north of the Ebingen source (Schneider, 1979). In many other parts of the world, a 25 km difference between epicenters of earthquakes occurring in 1827 and 1911 would not be resolveable, and the earthquakes would have been assigned to the same source.

Aftershocks: The well-studied 1979 aftershock sequence expanded along the strike of the fault plane of the mainshock in the week following the mainshock; many of these aftershocks probably occurred on the mainshock fault beyond the boundaries of the surface that ruptured in the mainshock. Later aftershocks occurred also off the fault plane (Haessler and others, 1979). The focal mechanisms of nearly all aftershocks agreed with that of the mainshock.

Differences: The Ebingen source is very near the Alps and the regional tectonic stress probably derives from the nearby collision of the African plate with the Eurasian plate (Ahorner, 1975). The regional stresses may therefore be more typical of plate boundary regions than of midplate regions.

H) Accra, Ghana (Figure 2): The west coast of Africa near Accra experienced strong earthquakes in 1862, 1906, and 1939 (MS = 6.5).

Depth: Recent small shocks from the zone of most intense shaking in the 1939 earthquake have focal depths ranging from near surface to 16 km (Bacon and Quaah, 1981).

Focal Mechanism: The focal mechanism of the Accra shocks cannot be reliably determined because of the sparseness of P-wave first motions for the 1939 earthquake and for the locally recorded small earthquakes. Tentatively, a shallowly dipping, northeast striking, normal fault, down to the southeast, agrees with a number of observations: (a) the 1939 earthquake was accompanied by an 18 km long zone of surface fractures which geologists at the site thought could not be attributed to slumping, and across which the southeast block was dropped with respect to the northwest (Junner, 1941), (b) the epicenters of recently recorded small earthquakes and the region of most intense damage in 1939 are on the downdropped block of the zone of fractures, and (c) first-motions of recent small earthquakes are consistent with slippage on a northeast-striking, shallowly southeast-dipping, normal fault (Bacon and Quaah, 1981). Such a mechanism for the 1939 earthquake would not be significantly less consistent with observed P-wave first motions than the strike-slip focal mechanism preferred by Bacon and Quaah (1981). Bacon and Quaah (1981) cite Burke (1969) as having previously suggested a northeast trending normal fault, down to the southeast, as the causative fault for the 1939 earthquake.

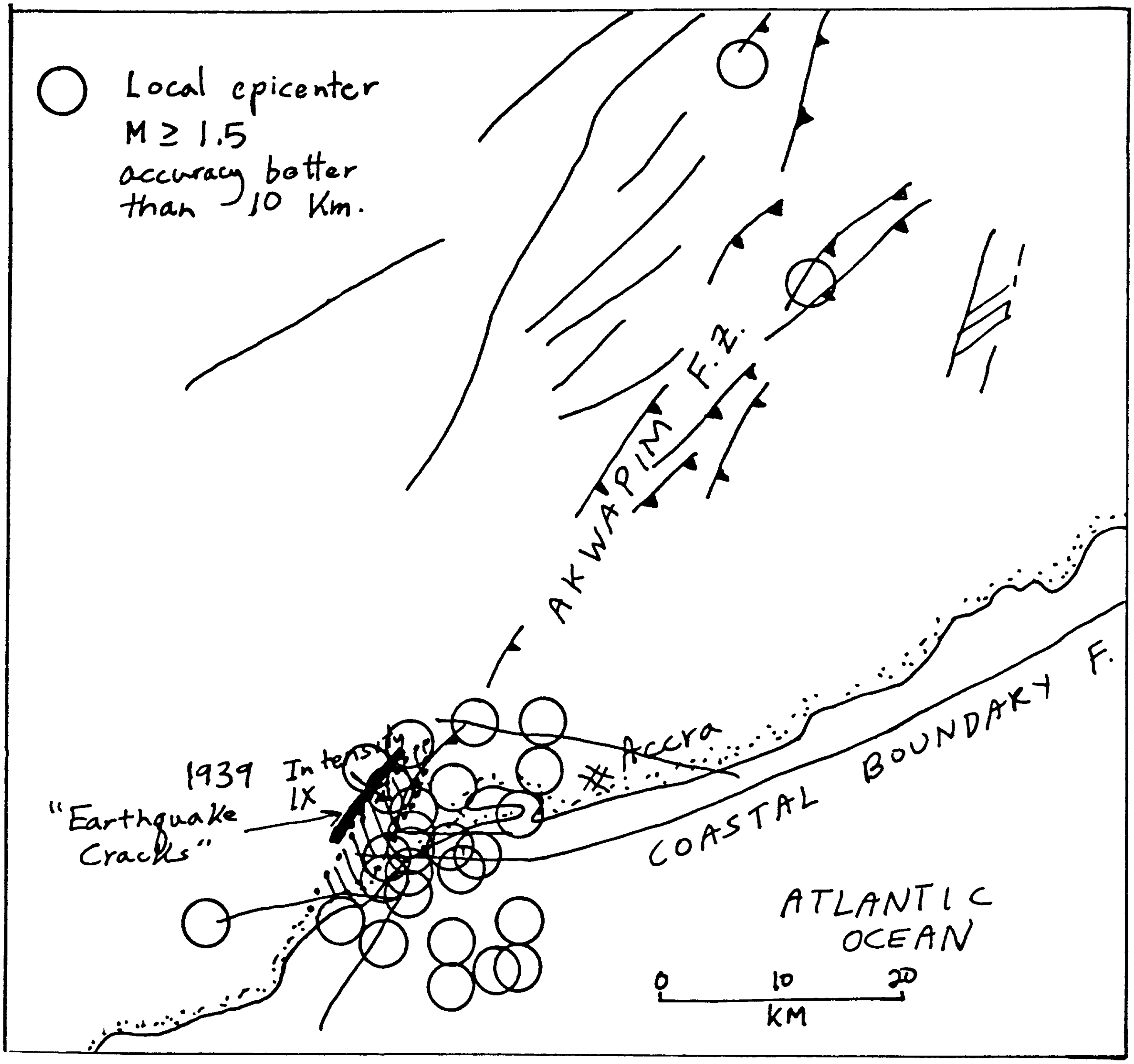

Figure 2.--Seismicity near Accra, Ghana, based on Bacon and Quaah(1981). The zone of 1939 earthquake cracks is taken from Junner(1941); the zone of cracks apparently extended about eight km farther to the southwest, beyond the boundary of Junner's (1941) map.

Preexisting Faults: The inferred fault of the 1939 earthquake would have the same strike as neighboring, mapped, Precambrian or Paleozoic reverse faults of the Akwapim fault zone (Burke, 1969; Bacon and Quaah, 1981). Burke (1969) suggested that some of the old reverse faults had been reactivated as normal faults.

Repetition: Although Accra had been damaged prior to the 1939 earthquake, in 1862 and 1906, the distribution of intensities reported for the earlier shocks (Junner, 1941) would permit these shocks to be located many tens of kilometers from the source of the 1939 earthquake.

Differences: Accra sits near the eastern terminus of the Romanche Fracture Zone and near a late Precambrian-early Paleozoic suture zone (Sykes, 1978). In addition, the Accra source is in an area with appreciable regional relief and it is near the continental shelf. It is possible that normal faulting earthquakes could occur near Accra due to high relief and large variations in crustal thickness across the continental margin (Bott and Dean, 1972) but that this mechanism would not be applicable to the Charleston region.

l) Ceres, South Africa: The earthquake of September 29, 1969 had a magnitude (MS) of 6.3.

Depth: Aftershocks to the 1969 earthquake were in the upper 10 km of the earth's crust (Green and Bloch, 1971), implying a similar depth for the main shock.

Focal Mechanism: The Ceres mainshock had a strike-slip focal mechanism (Green and McGarr, 1972).

Preexisting Faults: The causative fault was not identified from geological evidence (Green and Bloch, 1971). Faults with strike similar to that of the fault plane of the earthquake have been mapped in the epicentral region; most of these are normal faults, but some show evidence of a large component of horizontal motion (J.N. Theron and H.N. Visser, cited in Green and McGarr, 1972)

Previous Smaller Earthquakes: Fernandez and Guzman (1975) assign several previous small or moderate earthquakes to within ten's of kilometers of the Ceres source.

Aftershocks: Although the aftershock zone has the dimensions and planar configuration that would be expected for the causative fault of the Ceres earthquake (Green and Bloch, 1971), the strike of the aftershock zone differs by about twenty degrees from the strike of the fault plane implied by the focal mechanism (Green and McGarr, 1972). Green and McGarr (1972) suggest that the mainshock may have occurred beneath the zone in which the aftershocks occurred and transferred stress to the upper crust, where the increased stress produced aftershocks on minor faults that did not rupture during the main shock.

J) Koyna, India: The earthquake of December 10, 1967, was the largest (M = 6.3) of a swarm of earthquakes triggered by the filling of a reservoir and is one of the largest examples, worldwide, of a man-induced earthquake.

Depth: The mainshock had a focal depth of about 4.5 km (Langston, 1976). Aftershocks had focal depths in the uppermost 12 km (Rastogi and Talwani, 1980).

Focal Mechanism: The mainshock occured as a consequence of oblique slip faulting that had a component of left-lateral displacement and a component of normal displacement (Langston, 1976).

Preexisting Faults: The causative fault seems not to have been identified from geological evidence (Langston, 1981). The earthquake occurred within 10 km of a major escarpment that has been hypothesized to be fault-controlled. The epicenter is in a region of faults inferred from LANDSAT imagery (Langston, 1981).

Prior Seismicity: As has happened with other cases of man-induced seismicity, the strongest earthquake was preceded by swarms of smaller shocks (Gupta and others, 1968).

Aftershocks: Aftershock activity, or small earthquake activity that was also induced by the reservoir but that was independent of the 1967 mainshock, occurred well away from the causative fault of the 1967 earthquake (Rastogi and Talwani, 1980).

Differences: Because activity at the Koyna source was reservoir-induced, some of the seismotectonic characteristics of the source may differ in significant ways from the Charleston source.

K) Western Australia (Figure 3): This region has experienced eight strong earthquakes since 1967. Discussion here will emphasize the South West Seismic Zone (Doyle, 1971), site of the Meckering earthquake of 1968 (mb = 6.0, MS = 6.8), the Calingiri earthquake of 1970 (mb = 5.7), and the Cadoux earthquake of 1979 (mb = 5.9, MS = 6.0).

Depths: Focal depths of recent strong western Australian earthquakes have been between 1 and 20 km (Denham and others, 1979).

Focal Mechanism: Earthquake focal mechanisms so far determined for West Australian earthquakes involve predominantly reverse faulting, with a component of strike-slip faulting. In the case of the 1968 Meckering earthquake, it has been proposed (Fitch and others, 1973; Gordon and Lewis, 1980) that the fundamental mechanism of the earthquake involved left-lateral, reverse, motion on a north-northwest striking fault. This fault would be parallel to regional geologic structure and to the trend of the South West Seismic Zone, but would differ substantially from the right-lateral thrust fault mechanism implied by surface faulting. The seismological data published by Fitch and others (1973) seem equally consistent with a focal mechanism similar to that implied by the surface displacements associated with the earthquake.

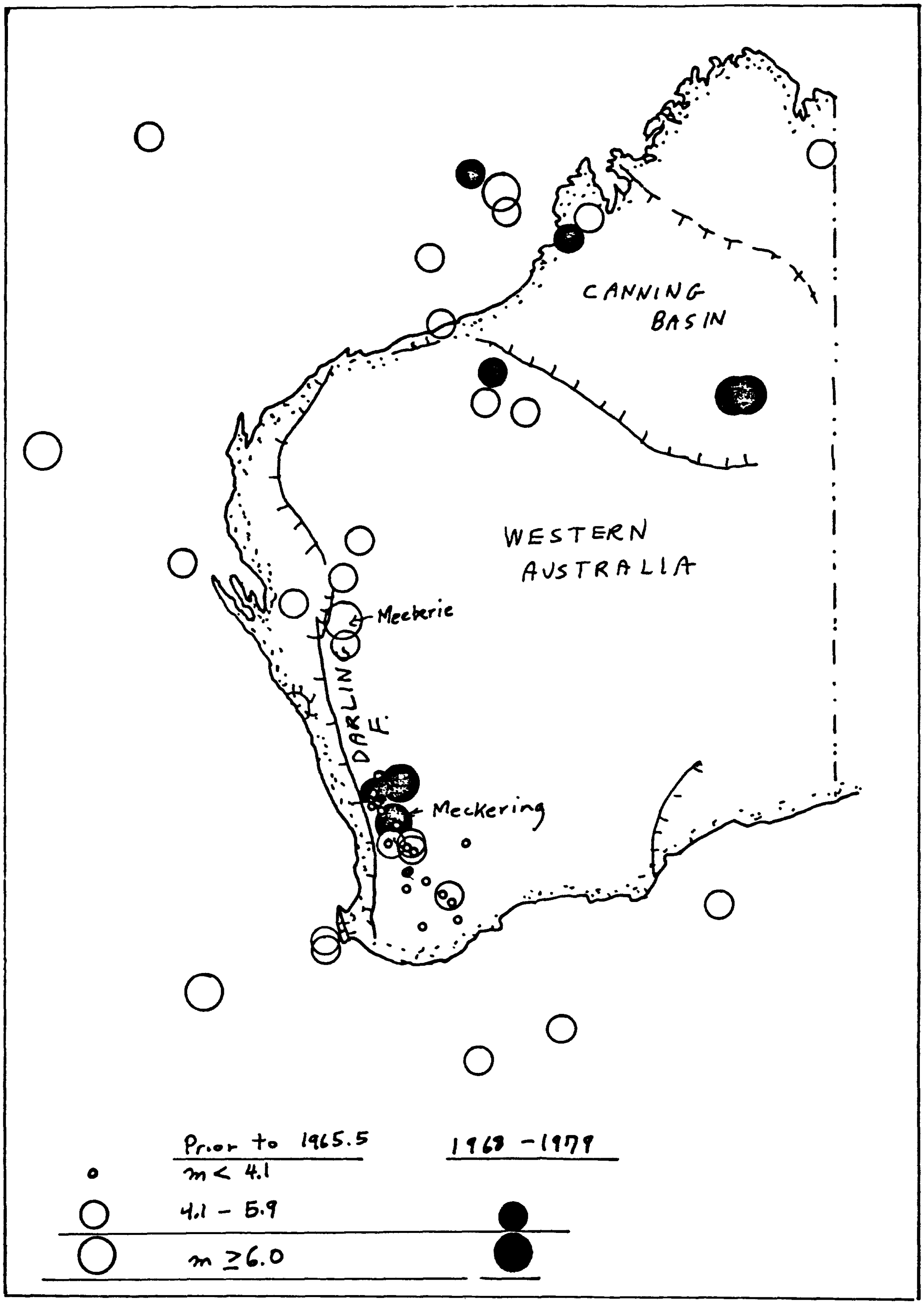

Figure 3.--Seismicity of Western Australia, based on Everingham (1968) with the addition of epicenters of strong shocks occurring in 1968-1979.

Preexisting Faults: Recent strong Western Australian earthquakes have not occurred on previously recognized faults. Retrospective analysis suggests that the Meckering fault was a reactiviated pre-existing fault (Gordon and Lewis, 1980).

Meckering is about 100 km from the prominent Darling fault, across which normal faulting occurred during the Mesozoic (Gordon and Lewis, 1980) (Figure 4). The north-striking Darling fault would seem to be favorably oriented to be reactiviated (e.g. Wentworth and Mergner-Keefer, 1981) by the current east-west compressional stresses (Denham and others, 1979), but the fault has been aseismic in historic times (Doyle and others, 1968). Recent seismicity in Southwestern Australia is mostly in the Archaen shield inland from the Darling Fault.

Repetition: The Meeberie earthquake of 1941 (MS = 6.8) occurred in Western Australia (Figure 3), north of the South West Seismic Zone, within tens of kilometers of a suspected fault scarp estimated to be approximately ninety years old (Gordon and Lewis, 1980).

Previous Smaller Earthquakes: The South West Seismic Zone, in which the 1968 Meckering, 1970 Calingiri, and 1979 Cadoux earthquakes occurred, had been identified as a seismic source zone (the "Yandanooka/Cape Riche Lineament") by Everingham (1968), prior to the 1968 earthquake. Some strong earthquakes after 1968 occurred in sources in Northwestern Australia that had also been identified by Everingham (1968) from earlier seismicity. Post-1968 earthquakes in the Canning Basin of Northwestern Australia occurred in a source that had not previously been identified by Everingham (1968), but Everingham had singled out this unpopulated region as one in which earthquakes might have occurred but not been detected by the pre-1968 seismographic network.

Aftershocks: The 1968 Meckering earthquake was followed by small earthquake activiity over an area roughly eight times as long and five times as wide as the source region of the 1968 main shocks as well as by strong earthquakes in 1970 at Calingiri and in 1979 at Cadoux, both removed from the source of the Meckering shock by a distance of approximately three times the source dimensions of the Meckering shock (Figure 4). There had been only one strong earthquake (1963, ML = 4.9, mb = 5.8) in the Southwest Seismic Zone in the preceding six decades (Everingham, 1968). Surface faulting at Calingiri (Gordon and Lewis, 1980) and Cadoux (Doyle, 1979) was similar to that at Meckering in being oblique-slip thrust faulting under the action of compressional stresses oriented approximately east-west, but differed in the sense of horizontal slippage (left-lateral at Calingiri in contrast to right-lateral at Meckering) or in the direction of overthrusting (overthrust to the east at Cadoux in contrast to overthrust to the west at Meckering).

In sum, a broad area of the South West Seismic Zone became active after the 1968 Meckering earthquake. In view of the modest level of seismicity prior to 1968, it seems plausible to consider the post-1968 seismicity as being in some sense aftershock activity to the 1968 earthquake. However, the areal extent of the zone of seismicity following the 1968 earthquake is surprisingly large. The differences in surface faulting observed with the three largest earthquakes, and the broad extent of the zone of seismicity during the period 1968-1979, indicate that the seismicity was not the consequence of propagation of slippage along a single fault.

Differences: Western Australia lies in the Indian Ocean plate, a plate with a rather high number of oceanic intraplate earthquakes, and it has been suggested (Sykes, 1970; Doyle, 1971; Fitch and others, 1973) that the seismicity of Western Australia is related to seismicity in oceanic portions of the Indian plate and is due ultimately to the configuration of the convergent plate boundaries to the north and east.

IMPLICATIONS FOR THE SOURCE OF THE 1886 CHARLESTON EARTHQUAKE AND FOR EASTERN UNITED STATES EARTHQUAKES IN GENERAL

In this section, reference is made to preceding regional discussions by the letters designating the regional discussions in the previous section. Thus, a reference to (K) is a reference to preceding discussion about Western Australia.

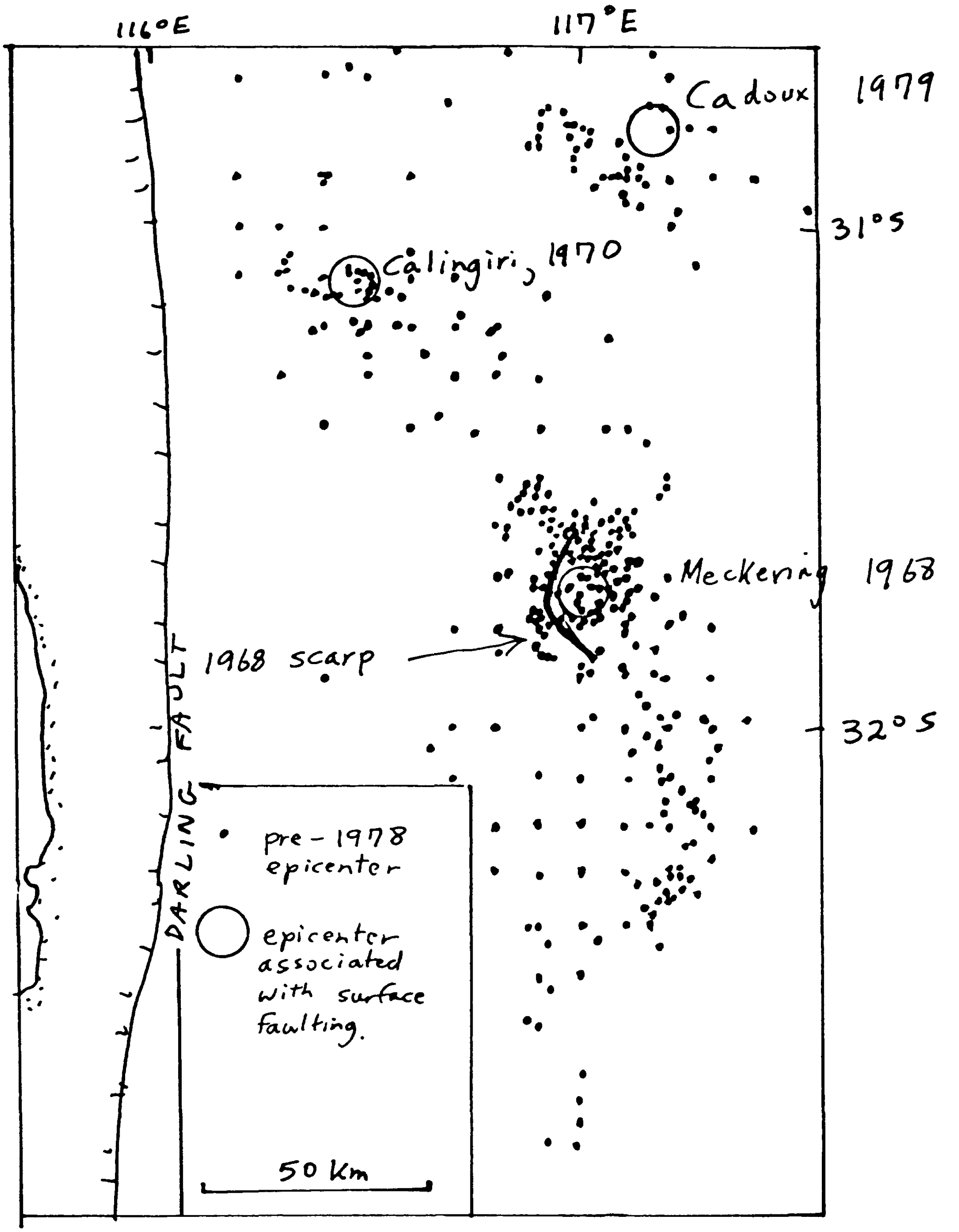

Figure 4.--Seismicity of the Meckering region, based on Denham(1979). Shocks occurring prior to Meckering 1918 earthquake may be included in pre 1978 epicenters. Post 1968 earthquakes extended at least as far south as 32.1° S (Gordon and Lewis(1980). 4131

Focal Depth: Many of the strong earthquakes considered in this review had focal depths in the uppermost 15 km, based on direct analysis of seismographic data (A, B, C, G, J), the presence of surface faulting (H, K), or the focal depths of early aftershocks (I). Although theory (Meissner and Strehlau, 1982; Sibson, 1982) and observations in some regions (C and possibly I) are consistent with the possibility that the midplate earthquakes may nucleate slightly beneath the depth of the deepest locally recorded microearthquakes and propagate to shallower depths from the point of initial rupture, the worldwide data do not provide grounds for postulating that midplate earthquakes originate at depths substantially below those of the locally recorded microearthquakes. By inference, the fault rupture causing the 1886 Charleston earthquake probably nucleated at or slightly below the depth of the deepest locally recorded microearthquakes (13 km, Tarr and Rhea, 1983) and propagated to shallower depths. We would therefore expect that the 1886 source would extend to depths shallow enough to be explored by geological or geophysical methods. The difficulty of locating the causative fault of the Charleston earthquake is probably not due to the focal depth of the earthquake, but to another cause such as the low frequency of large earthquakes on the causative fault during the Cenozoic.

Although it seems likely on physical grounds that very shallow sources of small earthquakes would not be likely to produce strong earthquakes (Sbar and Sykes, 1977), the global data do not resolve a minimum depth for strong midplate earthquakes.

Focal Mechanisms: There is enough variety in the types of focal mechanisms determined for other midplate regions that none of the focal mechanisms proposed specifically for the Charleston region can be ruled out on the basis of being outrageously incompatible with results from the other regions. Either similar mechanisms have been found elsewhere, or the mechanism proposed for Charleston is mechanically plausible in light of focal mechanisms obtained elsewhere. For example, Wentworth and Mergner-Keefer (1983) propose that the Charleston earthquake occurred as reverse faulting on a formerly normal fault; the La Malbaie source (B) and the Accra, Ghana, source (H) are examples of other sources that are most plausibly explained by reactivation of ancient faults under the action of a contemporary stress field that is oriented differently than the stress field that originally produced the faults. Focal mechanisms of earthquakes in Baffin Island (A) and Accra (H) are consistent with, though they do not require, low-angle normal faulting of the type postulated by Seeber and Armbruster (1981) for the Charleston earthquake. However (see the subsequent subsection entitled "Aftershocks"), Seeber and Armbruster's (1981) suggestion that a large aftershock region for the 1886 earthquake implies an equally large source for the 1886 mainshock is not justified by data from other midplate locations. The mechanism for the 1886 earthquake proposed by Behrendt and others (1983), involving reverse motion on a nearly horizontal decollement, probably cannot be ruled out if normal motion on a nearly horizontal surface is permissible in some midplate regions. Strike-slip faulting at depth beneath a zone of dip-slip surface faults has been found at the Ebingen source (G), at Ceres, South Africa (I), and postulated for the Meckering earthquake (K); this type of faulting would be similar to that postulated for the Charleston earthquake by Talwani (1982).

The existence of a particular type of faulting at another location cannot be used to justify ignoring evidence against that type of faulting at Charleston, but the existence of a particular type of faulting at the other location does demonstrate that there is precedent for such faulting in a midplate environment.

Preexisting Faults: There was not a strong tendency for the shocks to occur on prominent pre-existing faults that had been mapped prior to the earthquakes. As at Charleston, it has often been difficult to locate the causative faults even in retrospect. However, several observations point to the earthquakes occurring on preexisting geological structure in the upper crust, and some of these observations give hope for developing a better correlation between geological structure and seismicity. First, the shallow focal depths of many midplate source regions indicate that they are occurring in the upper crust. Second, a number of the strong midplate earthquakes occurred on faults that had similar trends to those of prominent pre-existing faults that are located within tens of kilometers of the earthquake fault, suggesting that the shocks occurred on concealed faults that were produced by the same stress system as had produced the previously mapped faults. Examples of such similarity in trends between earthquake faults and previously mapped faults are in the Accra region (H) and the Ceres region (I). Third, some large midplate source regions, such as the Mississippi Embayment source (E) and the La Malbaie source (B), are defined by distributions of epicenters that are parallel to faults in paleo-rift systems within which the earthquakes occur, notwithstanding that the epicenters have not been shown to fall precisely on mapped faults. Fourth, in some midplate sources, detailed retrospective studies have found evidence that the earthquakes occurred on preexisting structures that might have been mappable before the earthquakes; examples of such source regions are the Mississippi Embayment (E), Ebingen (G), and Meckering (K) sources.

The lack of seismicity on the Mesozoic Darling fault in Western Australia (K) and the corresponding high level of activity in the Archaen terrane to the east of the Darling fault may point to a situation similar to that near the Ramapo fault in the Eastern United States, where many small earthquakes occur away from the major Mesozoic faults (Ratcliffe, 1982). If the analogy between the Eastern United States and Southwestern Australia is valid, the Australian data suggest that large Eastern United States earthquakes could occur well away from major Mesozoic faults.

Repetition: Several of the source regions discussed have produced more than one strong earthquake in recorded history. Characteristics of seismicity in the Mississippi Embayment (E), Ebingen (G), and Meeberie, Western Australia (K) support the hypothesis that the repitition of strong shocks within decades or a few centuries from a given source region is the result of rupture on distinct faults or fault segments and does not imply that elastic strain is being rapidly accumulated and then released on the same fault segment. The precision of data from La Malbaie (B) and Accra (H) would permit historical strong earthquakes from these sources also to have occurred on distinct fault segments. These results imply that a strong earthquake in a future decade in the Charleston area is possible, but that such an earthquake would probably occur on a fault segment that did not rupture during the 1886 earthquake.

The worldwide data also provide examples of strong earthquakes at sources that had not historically experienced strong earthquakes (C, D, F, I). The Ebingen source (E) is an example of a source that had not historically produced a strong earthquake prior to 1911 but that became a persistent source of activity following the 1911 earthquake.

Granting that we cannot be sure that one midplate site is immune to future large earthquakes and that another will be exposed to large earthquakes, the worldwide data suggest that the liklihood of a future strong earthquake near Charleston is higher than at a random point in the Eastern United States, simply because Charleston experienced such an earthquake in the historical past. There have been relatively few strong midplate earthquakes worldwide, and, of those that have occurred, an appreciable fraction have occurred near sources of past strong earthquakes. What is uncertain is the magnitude of the difference between the liklihood of a strong earthquake near Charleston and the liklihood of a strong earthquake at a random point in the Eastern United States.

Previous Smaller Earthquakes: The global data seem generally consistent with the position often taken in seismic risk studies in eastern North America (e.g. Algermissen and Perkins, 1976; Basham and others, 1979); strong midplate earthquakes tend to occur in broad zones that had been previously defined by smaller shocks, but some strong shocks occur well away from previously identified sources and must be considered surprise earthquakes and treated as though they were part of the "background" seismicity. Unfortunately, the tendency for strong shocks to occur in regions of small earthquakes is presently of limited use, because small earthquakes occur over broad areas and because seismographic coverage of many regions is not adequate to detect small earthquakes. Continued research is needed to discriminate harmless sources of small earthquakes from potentially dangerous sources of small earthquakes.

I would cite Ceres, South Africa (I), many of the sources in Western Australia (K), Fennoscandia (F), and Ebingen (G), as examples of regions in which small earthquakes occurred close to subsequent strong earthquakes. The source regions that have produced repeated strong shocks (discussed in the previous section) would also presumably qualify as source regions which, after the occurrence of the first known strong shock, could have been identified from small aftershocks of the the first earthquake before the occurrence of the second strong earthquake. The Miramichi earthquake (C) would be an example of an earthquake that did not occur within tens of kilometers of a well-defined region of previous small shocks, but the occurrence of this earthquake is consistent with a previously defined tendency for small and moderate earthquakes to occur over a broad area of northern New England and New Brunswick. The 1935 Timiskaming, Quebec earthquake (D) must be considered a surprise earthquake in the present state of our knowledge.

Aftershocks: Many of the aftershock sequences reviewed here did not satisfy the characteristics of "normal" aftershock sequences defined in the section entitled "GENERAL COMMENTS ON PARAMETERS BEING STUDIED". Some mid-plate sequences occurred over regions substantially larger than the source volume of the mainshock. Well-documented examples of this phenomenon occurred with the Miramichi earthquake (C), the 1979 Ebingen earthquake (G), and, most dramatically, with the Meckering earthquake (K). Many small earthquakes from Koyna, India (J), occurred away from the mainshock fault plane, although in the case of this reservoir-induced earthquake it is easy to visualize that water diffusing from the reservoir might have triggered small earthquakes that were independent of the mainshock of December 10, 1967. Many aftershocks of the Ceres, South Africa, earthquake of September 29, 1969 may also have occurred off the fault plane of the main shock (I).

The second characteristic of a "normal" aftershock sequence, the tendency for current activity within the source of a strong earthquake to decrease to the background level of activity within several years (for the sizes of earthquakes considered in this report), is extremely difficult to test, since it requires definition of both "current activity" and "background activity", and both of these activities are stochastic variables that are, in addition, very sensitive to arbitrary assumptions. Two candidates for anomalously long-lasting aftershock sequences would be the 1933 Baffin Island source (A) and the 1939 Accra source (H), although in both cases the background level of activity prior to the strong earthquake is unknown.

The global data are not inconsistent with the suggestion (Tarr, 1977; Bollinger, 1983) that current activity at Middleton Place - Summerville may be aftershock activity to the 1886 earthqukake, in the sense that the current activity represents a delayed response to strain changes caused by the 1886 earthquake. If this is so, the global data support the suggestion by Wentworth and Mergner-Keefer (1983), that the current activity may provide a very distorted representation of the spatial configuration of the 1886 source. The extended "aftershock" zones associated with the 1968 Meckering, Australia, earthquake (K) and the 1982 Miramichi, New Brunswick, earthquake (C), and the fact that the fault dimensions of these earthquakes were not anomalously large, imply that the extended aftershock zone identified for the Charleston earthquake by Seeber and Armbruster (this volume) may be much larger than the source of the Charleston mainshock.

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INVESTIGATIONS OF THE NEW MADRID SEISMIC ZONE AND THEIR POSSIBLE RELEVANCE TO THE CHARLESTON SEISMIC REGION

by

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INTRODUCTION

The principal charge given to the panelists in Session IV of this workshop was to discuss "......what can be learned about Charleston from other large intraplate earthquakes." Before any discussion can be presented rationally, however, several rather obvious tenets should be remembered. The first is that estimation of the seismic hazard of any region requires knowledge of the location of seismogenic zones and the recurrence interval of earthquakes in the zone. The second is to recognize the tectonic, seismologic, and surface geologic similarities and differences among the various regions with intraplate earthquakes and the Charleston, South Carolina, region.

The first tenet is so well known no elaboration should be needed. Fulfilling this requirement however is the major problem to be resolved for all earthquake zones.

The second tenet as applied to a comparison of the New Madrid region to the Charleston area is more complex and may be summarized as follows:

1. No seismogenic faults have been recognized at the surface in either area, possibly because of cover by geologically young sediments. Other good reasons could also be given, however.

2. Attenuation of seismic waves is low, which may indicate regional similarities of crustal properties.

3. The epicentral areas are underlain by unconsolidated and semiconsolidated sediments.

4. The tectonic framework of each area is quite different. The Charleston region is underlain by structural elements associated with continental separations and collisions. The New Madrid region is underlain by an intracontinental rift, which may be part of an aulocogen whose southern extension is apparently obliterated by subsequent tectonic events.

5. Seismic activity is much greater in the New Madrid region than in the Charleston region.

The above five comparisons include information acquired during investigations of the regions during the past seven or eight years. So, we are not now starting from scratch to recommend new studies that may help resolve long-standing problems in the Charleston seismogenic tectonic zone and its temporal behavior. As we have learned more about similar problems in the New Madrid region than in the Charleston region, a statement of the problem there and a chronological account of studies and the logic for them may be useful.

THE NEW MADRID PROBLEM

Until about 1974, alignments of epicenters on small-scale maps and some local fault trends led some scientists to believe that the New Madrid seismicity was related to a major fault zone extending from the upper Mississippi embayment through the Anna, Ohio, epicentral area to the St. Lawrence Valley. This concept was based upon a crude alignment of diffuse seismicity. No substantive geologic information supported the concept, but it also could not be disproven. The problems to be solved were to determine more accurate locations of earthquakes, to delimit geologically the seismogenic faults or fault zones, and to determine recurrence intervals of earthquakes in seismogenic fault zones. The problems were compounded because our knowledge of and experience with intraplate seismic zones was very meager compared with seismically active zones along plate margins.

METHODS OF INVESTIGATION

With the establishment of the seismic network by seismologists at St. Louis University, the accuracy of hypocenters was greatly improved. Well defined trends of seismicity indicative of fault zones were clear in epicentral maps made from the network data. About a year earlier, detailed gravity surveys sponsored by the USGS had been started. Also, in 1974 I started searching, both through literature research and fieldwork, for evidence of surface faulting. This proved to be almost a waste of time, but was a necessary education. I concluded that whatever secrets the surface geology had to tell about earthquakes would be found by someone with expertise in geomorphic studies of major river valleys. David Russ provided this expertise and made several major contributions.

More or less concurrently with Russ's work, a small-scale refraction study under Jack Healy's and Mark Zoback's direction was conducted to locate suspected faults along the east side of Crowley's Ridge, beneath a lineament near Ridgely, Tennessee and beneath a scarp in the Reelfoot Lake area. This study was followed by 32 km of seismic reflection profile data acquired in the Reelfoot Lake area. Somewhat before, and concurrently with acquisition of the seismic exploration and geomorphic data, much gravity and aeromagnetic data had been acquired and was being interpreted. Integration and interpretation of all of these data indicated that the New Madrid seismicity was related to reactivation of geologic structures in a buried ancient rift. This interpretation was a major breakthrough in our understanding of the structural framework to which the New Madrid seismicity might be related. In order to determine more precisely the apparent subsurface seismogenic fault zone, about 240 km of seismic reflection data were contracted. Nearly all of the above studies and more are described in a summary volume edited by McKeown and Pakiser (1982). The last major study completed was a large-scale seismic refraction project using 100 seismometers to record a number of large explosions (Mooney and others, 1983). Studies in different stages of completion are: 1) the interpretation of Mini-Sosie seismic reflection data collected over suspected shallow subsurface faults; 2) completion of processing and interpretation of Mississippi River seismic reflection profiles; and 3) completion of processing and interpretation quantitative geomorphic information on streams in approximately 21,000 km^2 of the eastern Ozark Mountains.

The most important results of the above studies are summarized as follows:

1. As noted above, more accurate hypocenters from the seismic network defined trends of seismicity well enough to postulate the location of seismogenic fault zones.

2. Analyses and interpretation of aeromagnetic and gravity data indicated that most of the seismicity is occurring in a buried Precambrian rift.

3. A variety of geologic studies of surface and near-surface features such as scarps, sandblows, and suspected faults showed: (a) a recurrence interval of about 600 years for earthquakes strong enough to produce liquifaction, (b) minor Holocene faulting, (c) nearly all faults reported as Holocene in the literature are landslides.

4. The small-scale refraction surveys to identify faults along the east side of Crowley's Ridge and the Ridgely lineament show that these features are not related to faults. Drill hole data also showed that the east side of Crowley's Ridge is not faulted. A fault was interpreted in the refraction survey across the Reelfoot scarp. The small amount (32 km) of seismic reflection profiling indicated several subsurface faults, one of which is coincident with the Reelfoot Lake scarp.

5. The 240 km of seismic-reflection survey showed a major fault zone, about 9-km wide, below the top of Paleozoic rocks and coincident with epicenters in the southern part of the New Madrid seismic zone. A few faults offset the Paleozoic upper Cretaceous contact here and elsewhere, but the common lack of faults offsetting this contact was unexpected and possibly of more significance than currently recognized. One interpretation is that very little faulting has occurred since the upper Cretaceous and very long recurrence

intervals of faulting during this time (about 100 million years) can be inferred.

6. The detailed large-scale refraction survey confirmed the deep crustal structure within and outside of the rift. Prior to this survey, interpretation of gravity data and analysis of Rayleigh-wave dispersion suggested much less precisely an intrarift crustal structure similar to that derived from the refraction survey.

The above summary is only the major results of multidisciplinary studies designed to gain some geologic understanding and temporal characteristics of the New Madrid seismic zone. Many details have been omitted, and certainly all questions have not been answered. New information is slowly being acquired, and more detailed, perhaps some new, interpretations will continue in the future. This is likely because geologic information is commonly useful to many people with varied interests. For example, investigation of the New Madrid earthquake zone has already resulted in a major exploration effort for oil or gas resources in the rift first inferred and delimited by the aeromagnetic and gravity surveys. Eventually, though not in the near future, much of the oil exploration data will probably become available.

RECOMMENDATIONS

Even though the Charleston region is somewhat geologically and seismologically different from the New Madrid region, a number of the New Madrid investigations may be relevant to gaining an understanding of the Charleston region.

The following recommendations are based largely upon some of the most significant results of investigations in the New Madrid region and two general concepts. The concepts are: (1) that changes in strain accompany seismicity and (2) that arguments for a unique cause for the seismicity in the Charleston region cannot be made if all studies are limited to the Charleston region.

1. Very careful monitoring of seismic activity is essential, particularly because seismic activity is low.

2. Changes in strain (vertical or horizontal) over long (thousands to millions of years) and short (tens of years) terms should be sought in the Charleston region and a few other selected seismic and aseismic regions in eastern United States. The long-term detection may be done by quantitative geomorphic methods. With the exception of a few scientists, these methods have not been utilized with the rigor and imagination needed to realize their value to detect geologically young crustal deformation. Hack (1973 and 1982) has interpreted such deformation in the Piedmont and Blue Ridge. Russ (1982) has essentially proved Holocene uplift in the vicinity of New Madrid, though it had been suggested without substantive data for many years by other investigators. One of the most recent uses of quantitative geomorphology in Eastern United States is by Mayer and Wentworth (1983) who demonstrate geomorphic difference east and west of the Stafford fault system in northeastern Virginia. Preliminary interpretation of part of the quantitative geomorphic study of the eastern Ozarks by me and my colleagues suggest both the identification of deformed areas and faults. The short-term detection may be done by compilation and analysis of horizontal and vertical geodetic measurements. Interpretation of these measurements have been fraught with problems, but resolution of the problems should be achievable.

3. The determination of a recurrence interval of about 600 years for events strong enough to cause liquifaction of sediments in the New Madrid area was based upon cross-cutting relations exposed in a trench that intersected sandblows. The 1886 Charleston earthquake caused sandblows over a large area. Some of these should be located and a few, selected upon geomorphic and sedimentological features, should be explored by trenching, mapped, and studied in detailed. Furthermore, photo reconnaissance study of all major river valleys where conditions are favorable for liquifaction of recent sediments should be made. This study will require field checking of selected areas and some exploration. If sandblows in environments favorable for liquifaction cannot be found, some minimum estimate of the

recurrence of strong earthquakes in the areas without sandblows can be inferred.

4. All available gravity, aeromagnetic, and seismic (reflection and refraction) exploration data for the onshore and offshore eastern seaboard should be utilized to determine whether the Charleston region is indeed structurally unique.

5. Serious consideration should be given to the question of why some faults are currently seismically active and others are not. The commonly expressed idea that earthquakes occur in weak fault zones is not incorrect; but it is also rather useless. Afterall, faults with the proper orientation to slip in the current stress field of any region are ubiquitous at many levels in the crust. The critical problem is to identify or infer the current special environment that is conducive to fault slip. For example, pore pressures changing because of alteration of rocks, volatilization of carbonaceous material at great depth, or changes in the hydrologic regime at great depths all could have an effect on the tendency of faults to slip. Local changes in the stress field as the result of stress concentrations around intrusives has been thought by some to be related to seismicity. This concept still merits consideration. In short, much more effort should be given to identifying processes conducive to fault slip and to identify or infer where these processes may occur than just to identification of seismically active zones without understanding them. Petrologic, mineral deposit, hydrologic, and related studies may be of much more significance to identification of current seismogenic zones than the identification of recent fault movement.

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A BASIS FOR COMPARING LA MALBAIE, QUEBEC TO CHARLESTON, SOUTH CAROLINA

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INTRODUCTION

The La Malbaie region has experienced some of the largest earthquakes on land in northeastern America. It has a 3 1/2 century long historical record with reported intensities VIII, IX, and X; its most recent large earthquake in 1925 has a magnitude m_bL_g = 6.6, very similar to that assigned to the 1886 Charleston event. La Malbaie is also among the first very active regions in the east to be monitored by local seismic networks; in addition, many of the geological and geophysical sciences have been used to study the tectonic causes of its seismicity.

Given our present concern about the significance of the Charleston seismicity and our relatively incomplete grasp of its causes, it is logical to review our current understanding of the La Malbaie tectonics in the hope that the parallel will yield interesting clues. My original intent was to report only on the seismological investigations at La Malbaie, and let those who are more familiar with the Charleston studies draw the similarities and differences. After listening for two days to the technical presentations and the resulting heated discussions, I conclude that some benefit might also arise from a description of the climate which surrounded the La Malbaie Program.

I realize that concerns about the safety of nuclear plants, operating or under construction along the east coast, have created for the U.S. Nuclear Regulatory Commission a pressing urgency for a clearer definition of the earthquake potential associated with Charleston. Such an urgent need never existed at La Malbaie and surely this explains why the investigations were carried out calmly and without animosity.

Much impatience permeated numerous presentations of this workshop; some speakers in their desire to emphasize the positive element of their contribution were either too aggressive in rejecting other models or claimed the truth with too much exclusivity. It was equally disturbing to hear requests for an experiment that would decide which model is the best and the truest, as if this were a realistic approach and the prime objective at this early stage.

By describing the La Malbaie Program, I hope to convince you that our efforts to understand the tectonic regime at Charleston will be successful only if they are conducted cooperatively through an honest dialogue and not turned into a contest. Each of us must accept that the true and full explanation might come only from more than one contributor.

The La Malbaie Research Program was initiated 15 years ago without fanfare by the Earth Physics Branch of the Department of Energy, Mines and Resources of Canada. It was a modest program in terms of total dollars; but somehow, maybe for that very reason, it served as a catalyst for numerous investigations by other government agencies and academic institutions.

Although the synthesis is not complete, substantial progress has been achieved in the understanding of the seismicity. The La Malbaie-Charlevoix seismic zone has been proposed and accepted; its earthquakes are considered to be structurally related, and thus not subjected to migration. As a consequence, the seismic hazard is defined with greater confidence than ever before. In my opinion, this is the major difference between La Malbaie and Charleston. In the first case, the earthquakes have been finally confined, while for Charleston, a new trend is to release them. This diffrence is the result of various interpretations of a tectonic structure and an acceptable correlation to structure.

ACHIEVEMENTS AT LA MALBAIE

1) Definition of the seismicity in space.

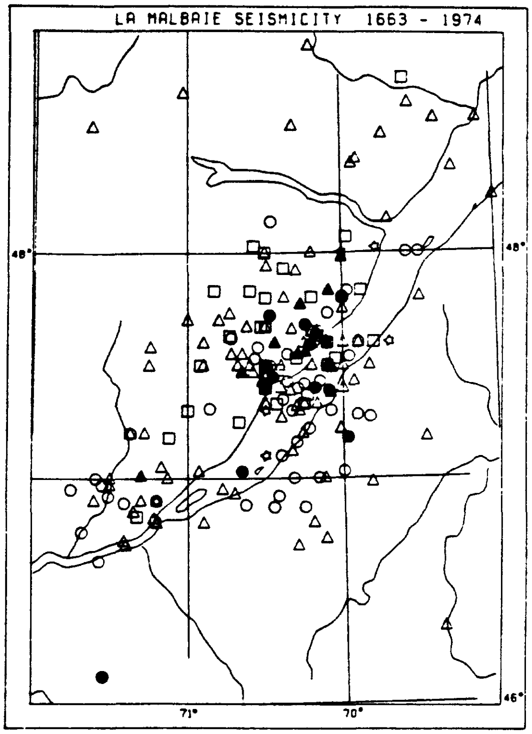
a) Through seismic monitoring.

The spatial definition of the sesismicity at La Malbaie was above all a progressive process. It was not accomplished quickly and without controversy. But undoubtedly, the key element was the acquisition of reliable hypocentral locations through dedicated seismic networks.

The pattern of historical seismicity shown on Figure 1 is so diffuse between Quebec City and Tadoussac, that one cannot truly predicate it to the La Malbaie region, except by association with the location of the well known 1925 event, and the historical tradition of frequent tremors felt in the area of Baie St. Paul and La Malbaie. Because of this recognized activity, the La Malbaie region had been labelled as a Zone 3, related to the highest seismic potential, on the seismic zoning map of the National Building Code of Canada. In this context, it was normal to choose that region for studying seismotectonic processes in eastern Canada.

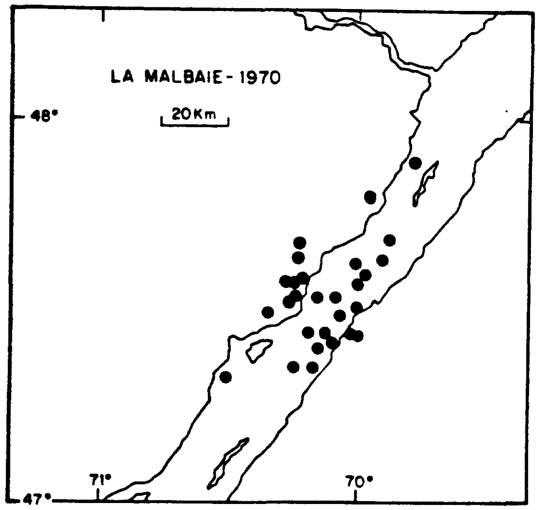
In 1970, following a feasibility study by Smith in 1968, (Milne et. al., 1970) a microearthquake survey was initiated in the La Malbaie region (Leblanc et al., 1973). The number of portable seismometers available was seven at the maximum and the configuration had changed periodically. The observed epicentral pattern (Figure 2) was surprisingly limited relative to the known historical distribution (Figure 1). The average of the focal depths was 10 km. The Earth Physics Branch had sufficient confidence in the data to considr these results significant and worth pursuing on a priority level.

In January 1972, permanent seismic monitoring began with a station at La Pocatiere, on the south shore, in cooperation with Laval University. Although small local events could be detected and rate of activity checked, another field survey was needed to confirm the 1970 boundaries of the active zone. A larger and



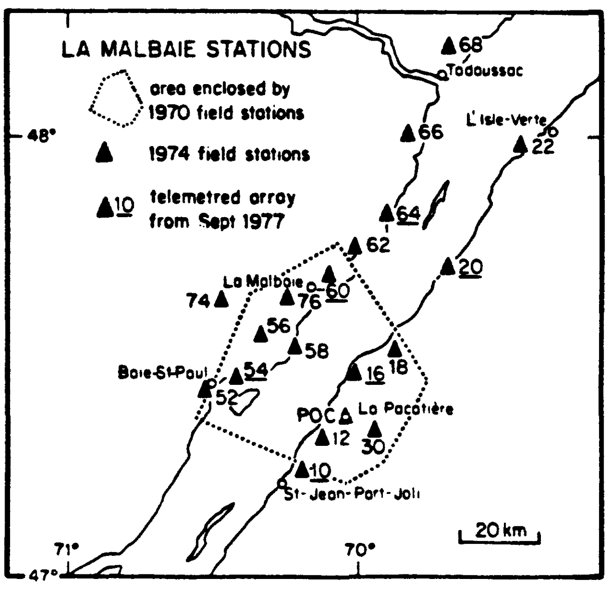
Seismicity of the St. Lawrence River Valley in the vicinity of the La Malbaie region. Symbols represent magnitude ranges: circle <3, $3\leq$ triangle <4, $4\leq$ square <5, $5\leq$ star <6, $6\leq$ circled star. Filled symbols represent more reliable positions. Microearthquakes are not plotted.

FIGURE 1



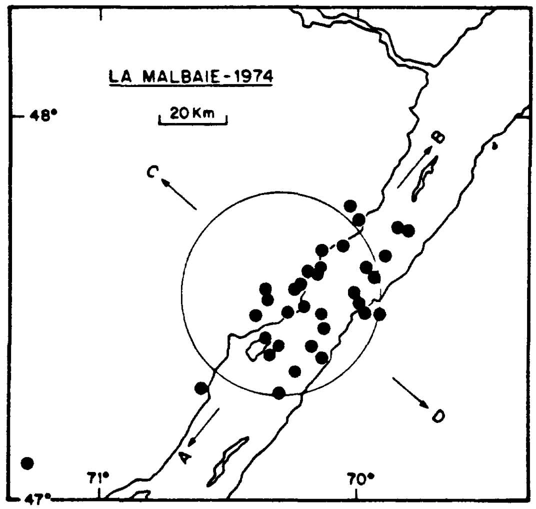
Epicenters of 1970 experiment.

FIGURE 2



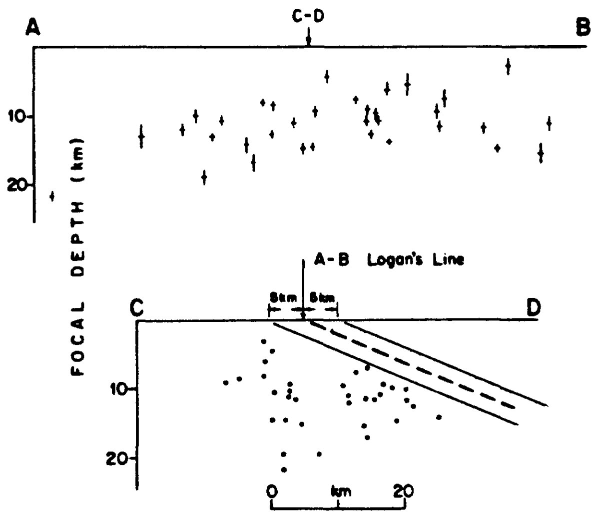
Recording sites occupied during the microearthquake survey of 1974 (after Leblanc and Buchbinder, 1977). POC is a regional station (SPZ) established in January 1972 and upgraded (3 *SP*'s) in September 1977. Regional station LMQ was installed in November 1976 at virtually the same site as field station 56.

FIGURE 3



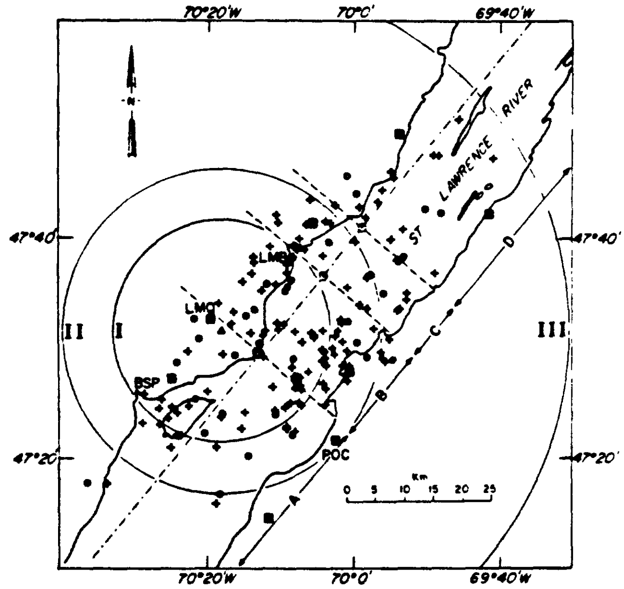
Epicenters of 1974 experiment. Circle represents outer boundary of Charlevoix structure.

FIGURE 4



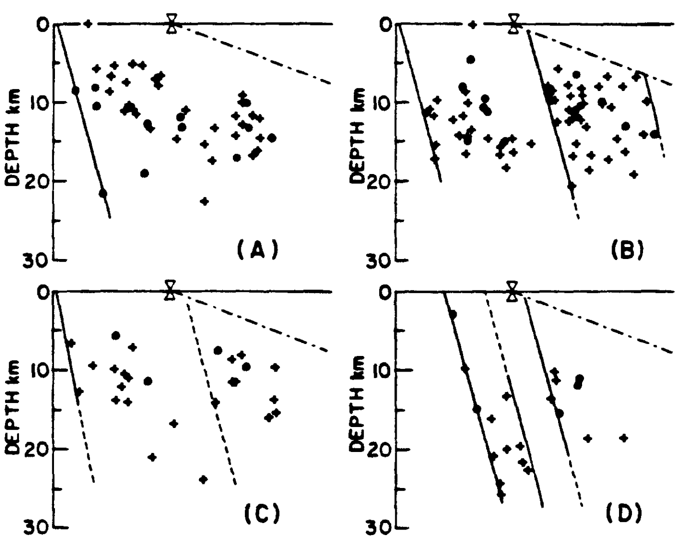
Hypocenters of 1974 earthquakes projected on planes A-B parallel and C-D normal to the St. Lawrence River The shaded zone represents uncertainty in Logan's Line and contact.

FIGURE 5



Region of mid-St. Lawrence Valley monitored for microseismicity. Locations of array seismometers, regional stations POC and LMQ, and local place names. St Lawrence River flows from *lower left* to *upper right* Epicentral locations 1974 data from Leblanc and Buchbinder (1977) are marked with ● 1977 to 1979 locations are marked by +. Region is divided into four zones (A to D) as marked by three dashed lines orthogonal to river. Fine dashed line along north shore is parallel to average trend of north shore normal faults Circular crater limits after Roy (1978).

FIGURE 6



Sectional plots of data of Figure 6 using same symbols. Perspective is from viewpoint looking downriver parrallel to fine dashed line in Figure 6. Dashed lines in upper right are the average contact of the overlying Paleozoic sediments with the Grenville crystalline basement. Lines dipping 75^{0} to the right (SE) indicate present seismicity boundaries.

FIGURE 7

centuries, and the linear configuration of the first seismographic stations of the national network, at least up to the mid sixties.

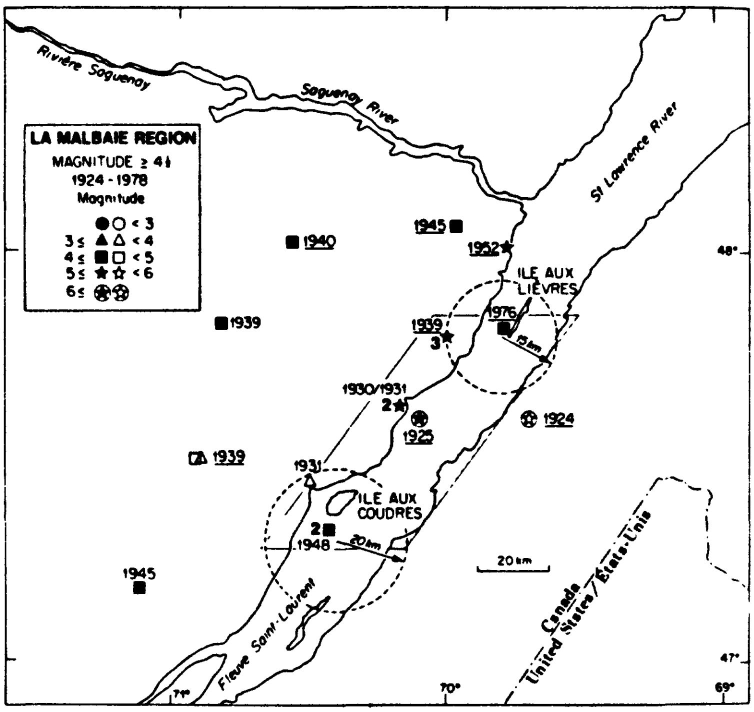
Pursuing this idea, Stevens (1980) has re-examined regional seismograms, both from Canada and the United States, and relocated 18 events, with magnitude greater than 4 1/2, from 1924-78. She found enough support in the data, not only to place the relocated epicenters within the active zone defined by the microearthquakes, but also to see them clustering near the extremities of the zone, particularly to the northeast, south of L'Ile aux Lievres (Figure 8). Dewey and Gordon (written communication), using teleseismic data, have also relocated some La Malbaie events near the northeast end of the microearthquake zone, in support of Stevens.

The occurrence of a moderate size event, $m_b = 5.0$ on August 19, 1979, just outside one of the clusters proposed by Stevens (1980) but inside the microearthquake zone, reinforces the pattern. It is also worth noticing that Hasegawa and Wetmiller (1980) calculated a focal depth of 10 km. Their preferred fault plane solution agrees with those of the 1974 microearthquakes (Figure 9); it also supports Anglin and Buchbinder's correlation of small events with old normal, steeply dipping faults.

2) Definition of the seismicity in time.

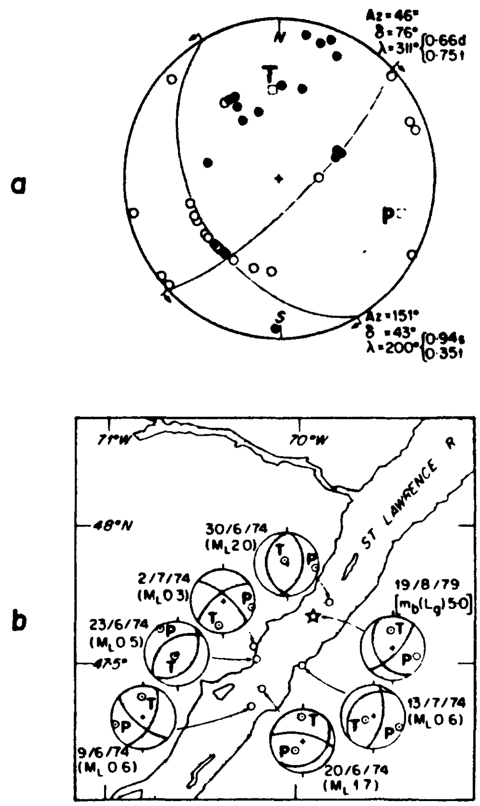
The definition of the seismicity in the time domain was also a gradual achievement. Even if the historical record was available in a catalog form (Smith, 1962, 1966) in the mid-sixties, a more reliable set of a- and b-values became possible after the active zone boundaries were clearly defined.

The La Malbaie region has a relatively long record of intensity data as it was populated in the early days of the French Colony. The first entry is Smith's catalog places a very large event in the region between 1534 and 1535, at the time of the discovery of eastern Canada



The 18 events studied for this report identified by year and magnitude range. See Table 1 for details. All known earthquakes in this region and period with magnitude ≥4½ are included. A boldface digit beside an epicenter gives the number of earthquakes with the same published epicenter. A filled symbol indicates an epicentral uncertainty not more than 40 km according to the relevant catalog. An open symbol indicates greater uncertainty. An underlined date denotes the 11 earthquakes relocated near Ile aux Lievres. The remainder (except June 1945) are relocated near Ile aux Coudres. The dashed circles mark the approximate source areas of the relocated events.

FIGURE 8



P-wave nodal solutions of (a) August 19, 1979, earthquake and (b) microearthquakes (open circles represent epicenters, star represents epicenter of August 19, 1979 earthquake) (from Leblanc and Buchbinder, 1977). Symbols are defined as follows: solid dot (in shaded region) denotes compressional and open dots dilatational first motions; P and T denote deviatoric compression and dilatation, respectively; Az is azimuth of strike; geographic north, N; δ refers to dip of fault plane, λ refers to angle (measured counterclockwise from strike) of direction of slip of footwall relative to hanging wall, components of which are represented by d(dextral), s(sinistral and t(thrust).

FIGURE 9

- 27 -

by Cartier. The location and size of this event are questionable; one may choose not to count it. With the founding of Quebec City in 1608, records of large regional events were assured through personal diaries of missionaries and public administrators; so the 1638 and 1663 events are most likely good data points. Since the St. Lawrence River shores, both upstream and downstream from Quebec, were among the first to be settled, no event in the La Malbaie region with an intensity VII or greater would have been missed, after 1700.

The instrumental detection around La Malbaie began early, since after the 1925 earthquake, the Dominion Observatory of Canada installed a station at Seven Falls and Shawinigan Falls. For a complete review of the development of the network in eastern Canada, one should refer to Basham, P. W., et. al. (1979) and Stevens, A. E. (1980). For many years, up to the seventies, the configuration of the Canadian network was not able to give the La Malbaie area accurate epicenters; yet the seismicity was still relatively well monitored. By using as a complement intensity reports from both shores of the St. Lawrence River, a good data set on the activity between Baie St. Paul and La Malbaie was collected. It should be noted that some of the epicentral intensity data were recently subjected to careful examination by the Earth Physics Branch; many magnitude values have been recalculated by Basham et. al. (1982).

The permanent on site operation of a six-element telemetered array, since 1977, has made it possible to calculate rates of small events, extending the recurrence curve and giving it a more representative b-value. The b-value for the La Malbaie area is relatively stable, about -0.70, whether time starts from year 1600 or 1700; the a-values are 2.43 and 2.44, respectively (Figure 10). Once both intensity data and M_L values are converted to the same m_bL_g scale, one finds the entire set remarkably consistent. The omission of the M_L values conversion, affecting mostly intermediate events, results in a 20 percent increase of the rates; this can be significant for hazard estimate.

3) Definition of Earthquake Causes

There are two classes of hypotheses proposed to explain the seismicity at La Malbaie. I do not wish to review them individually, but simply comment on their generic characters and practical value. In the first class, we have hypotheses which relate broad seismicity patterns to major geologic or tectonic structures. As examples of these, we could refer to Woollard's (1969) and Kumarapeli's (1978). In this scenario La Malbaie is only one of many seismic zones under consideration; the seismic activity near Montreal and Cornwall, near the Gulf of St. Lawrence, along the Ottawa-Bonnechere Graben, are all included in this broad association. In my opinion, such an approach, which at first seems to explain alot, leaves just as much open ended, since it does not explain the aseismic zones that are equally evident along the same rift zone. We have heard from L. Seeber that seismic gaps along the Aleutians are indeed more hazardous than the active areas, and that the same situation could exist along the Atlantic coast. In an absolute sense, nobody can prove at this time that it does or does not! Yet, because the concept of seismic gaps is originally related to interplate tectonics, where seismicity is observed in almost perfect coincidence with well mapped faults extending over large distances, caution is in order before applying the same concept to an intraplate environment, where the active structures are still poorly defined, where different type of faulting is common, and the possibility of block tectonics is now suggested.

For seismic hazard estimation, our prime objective indeed, this first class of hypotheses is somewhat impractical, as it requires beyond observed data some highly subjective assumptions to model the extent and predict the behavior of the aseismic regions. This subjective input can affect seriously the hazard results. At that point, the value of many years of empirical observations, leading for example to a sharper delineation of the true seismicity at La Malbaie, are lost in favor of a subjective opinion.

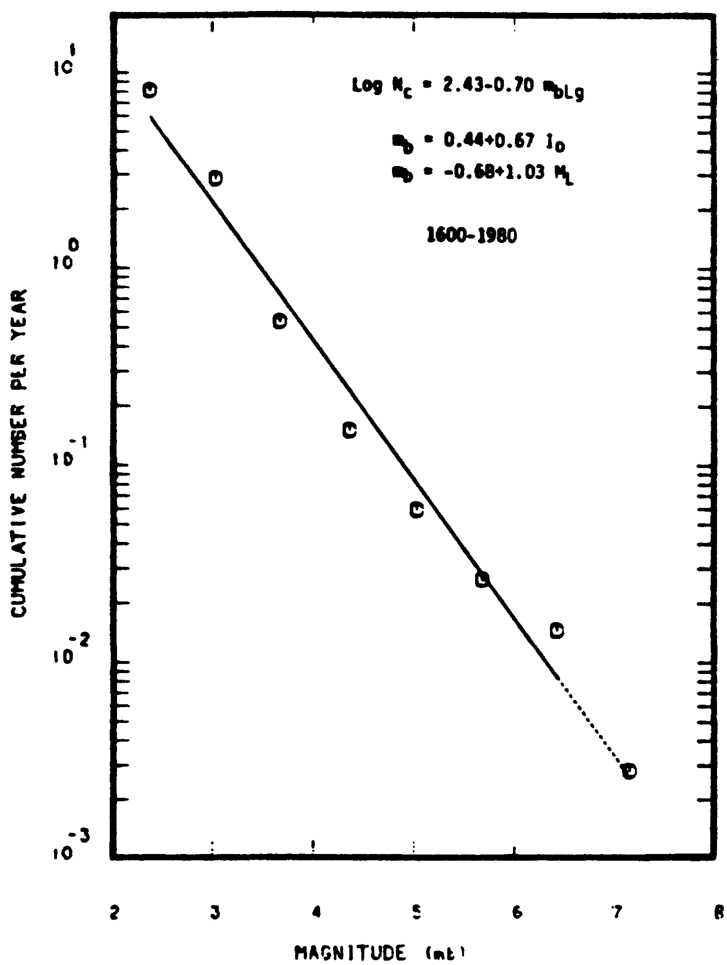
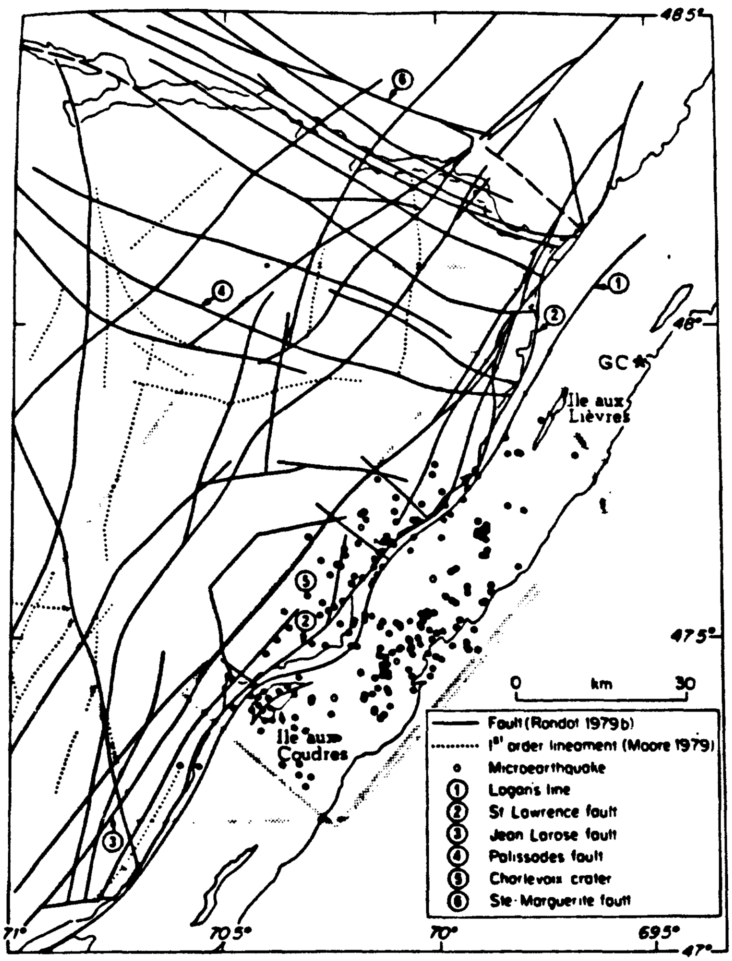

Log N_c = 2.43-0.70 m_bLg
m_b = 0.44+0.67 I_0
m_b = -0.68+1.03 M_L
1600-1980
CUMULATIVE NUMBER PER YEAR
MAGNITUDE (mt)

FIGURE 10



Microearthquakes and structural features in the region of the Charlevoix seismic zone.

FIGURE 11

In the second class, we find hypotheses that focus predominantly on local structures, or some conjunction of structures, to explain the restricted pattern of seismicity observed at La Malbaie. This type of approach is basically founded on the observed individuality (some critics would say "assumed") of the seismic zone, and the rationale that whatever causes earthquakes to occur in that limited area must also be specific to that same area. This is a sound principle with numerous applications in physical sciences. In this context, any spatial correlation of seismicity with an identified tectonic structure should be considered significant since it has the potential of being also a causal relationship.

I would agree with C. Stepp's earlier statement that "we need to go beyond spatial correlation," if it means that our aim is to demonstrate whether or not the identified structure is truly the cause of the earthquakes, and if so, explain the processes in terms of Physics. Setting up such a challenge can be beneficial as it provides stimulus and guidelines to research. Yet if its idealistic character is not recognized, frustration and panic will arise. To some extent, this is presently the case at Charleston. Maybe more has to be done on identifying the existing structures before arguing on their causative relationship with the earthquakes.

At La Malbaie, one still finds parts of the puzzle missing; yet the picture is sufficiently composed to establish beyond reasonable doubt that the La Malbaie zone has its own identity and prevent its seismicity, well defined in time and contained in space, to be diluted over the adjacent region. Somehow, the earthquakes are considered to be structurally correlated.

There are many geological structures at La Malbaie and its vicinity. Some have broad linear dimensions: e.g., faults associated with rifting; Logan's Line, a contact between two distinct geological provinces; some are more restricted, e.g., the Charlevoix impact crater, a circular and deep crustal structure (Rondot, 1968, 1979), including numerous related faults on the north shore; a zone of subsidence adjacent to a zone of postglacial uplift (Dunbar and Garland, 1975); numerous northeast- and northwest-trending faults (Figure 11) of different ages, some parallel to the St. Lawrence River and others parallel to the Saguenay River, etc. Many of these structures were individually considered as hypothetical causes of earthquakes, but their shortcomings are strong. For example, the long linear structures, such as Logan's contact and the paleorifting faults are only half answers in view of the apparent lack of activity outside the La Malbaie zone. The Charlevoix impact structure is active only over half of its circular domain and coincides only in part with the La Malbaie rectangular zone. Land faults show no recent surface motion; surface displacement on fault segments under the St. Lawrence, should it ever occur at the time of a large earthquake, may not be easily observed.

Fully aware of the limitations of simplified models, researchers now include serveral causative elements in their tectonic scenarios. A seismogenic structure is then interpreted as a combination of geological or tectonic features; the regions where these various structural or lithological elements interact or intersect constitute the crustal inhomogeneities that localize stresses and decouple adjacent rock masses.

In this new spirit, various combinations have been proposed by different authors; but more significant is the gradual evolution that can be seen in the same individuals. Some have paired local northeast-trending faults and the meteorite crater, (Leblanc et. al., 1973); some have pointed to the interaction of Logan's contact with the impact crater (Leblanc and Buchbinder, 1977; Lyons et. al., 1980); others have emphasized the importance of the rift faults (Anglin and Buchbinder, 1981); more recently Stevens (1980), and Basham et. al. (1982), have introduced a new element and implied that southeast trending faults across the river could play a role in localizing the activity south of l'Ile-aux-Lievres and forming the northeast boundary of the zone. A brief synthesis of the complex model is presented by Basham et. al. (1982). This type of model which incorporates contributions from geology, geophysics and seismology, and uses intersecting structures to explain an observed block-type zone of activity might be also applicable to other intraplate seismic zones, including the Charleston area. This is certainly in agreement with Bollinger's (1983) hypothesis that "the source zone of the 1886 Charleston earthquake is localized by the intersection of at least two seismogenic structures, one trending northwest and the other trending northeast". In a similar vein, Ratcliffe has invited us to "look for multiple causes in the same area".

IMPORTANT LESSONS FROM LAMALBAIE

1) Cooperative Program of Research

These definitions of the seismicity at La Malbaie have provided an accepted basis for seismic hazard estimation, both close to and away from La Malbaie. This is an extremely valuable result for engineering and public safety. This achievement was made possible because a true spirit of cooperation was supported not only by the individual researchers but also by a smaller group of key administrators whose names seldom appear in our references.

As mentioned earlier, the Earth Physics Branch Program was modest, but it remained open mind at all times. If I have stressed the results of the seismological studies, it was not to minimize the equal importance of the data, both geological and geophysical, collected by others. The approach was always multi-disciplinary. This is clearly attested by the establishment of a geophysical observatory on the north shore, the precise gravity and magnetotelluric surveys conducted. Seismic reflection-refraction surveys (Lyons et. al., 1980) were also made to support the structural model elaborated by geologists. Although the federal government was active through the Earth Physics Branch studies, it supported numerous university researchers through National Research Council grants.

The contributions from staff members of the University of Toronto, Laval University and the University of Quebec at Chicoutimi, and from the Quebec Provincial Government agencies, particularly the Department of Natural Resources and the Quebec Society of Petroleum Exploration, were all essential to the program. Somehow this diversity of viewpoints and jurisdiction did not result in sterile conflicts; instead it provided complementary talents, resources and data.

The Program at Charleston can become equally successful if a similar climate of cooperation is truly fostered by everyone, and premature attempts at synthesis are avoided.

2) Clear Definition of the Objectives

A second lesson from the La Malbaie studies is the importance of establishing and maintaining clear objectives for each of the studies undertaken. This is vital to the program. These objectives must be realistically defined, taking into account the limitations of a particular methodology used, the constraints of a budget, etc. If this basic rule of scientific research is not duly applied, confusion can arise.

One example may clarify the point. Because of a possible instrumental coverage bias during the 1970 survey, a second experiment was planned to establish the distribution of the seismic activity. This was the essential objective of the 1974 survey. Finding the causative mechanism of this distribution was not the goal of the survey. Similarly, the careful mapping of the north shore geologic structures was not directly oriented to explain earthquake occurrences. Conclusions of studies performed with clear objectives tend to be less speculative; they constitute data points in the analytic phase. The synthesis comes later. It is remarkable that most studies on different topics related to La Malbaie have abstained from strong or dogmatic wording when referring to a tectonic model.

This need for a clear definition of objectives and results bring me to discuss another source of confusion. Recently, in the context of licensing nuclear power plants and calculating seismic hazard, an equivocal expression has been used. We have heard of a Kentucky type event, an Anna, Ohio type event for the Central Stable Province of the United States. In 1982, we have been faced with a New Brunswick type event, for the northeast. In this workshop, we have been warned and concernd about a Charleston type event. The equivalent expression in Canada would be a La Malbaie type event. The usage of this expression is misleading! The relative magnitudes of these events are 5.1 to 5.3, 5.7 to 5.9, and 6.6 to 6.8, m_bL_g, respectively. For the Central Stable Province, broad but tectonically diversified, a Kentucky-Anna type event, must simply mean a 5.3 magnitude event, i.e. a reference to the size only, as no one assumes a single seismogenic structure throughout the province. In the case of a New Brunswick type event, besides the reference to the magnitude, 5.7 m_bL_g, there is clearly an additional connotation, i.e. that the causative structure of the January 1982 New Brunswick events may extend throughout the New England Piedmont-Northern Appalachian region and could typically cause events with a similar magnitude. The concern is on the structure, i.e. the cause of the earthquake. The concern about a Charleston type event is similar, and the emphasis is more on the possible extension of the causative structure along the coast than on the size of the event.

An effort should be made to clarify what is meant, as the input to hazard studies is affected by this ambiguity. The research programs to verify the extension of a given structure throughout a large region are different from those that establish the likely upperbound magnitude of a given structure.

At La Malbaie, the structure has been defined both in space and time. The upperbound is likely higher than 6.6 m_bL_g, but it is not to be shifted in space. At Charleston, for lack of concensus on the causative structure, both the maximum magnitude of the event associated with the structure responsible for the 1886 earthquake and the location of the structure itself remain open for discussion. For seismic hazard estimation, this uncertainty results in a wide range of predicted values; these extremes make almost no sense.

CONCLUSIONS

The seismic regime at La Malbaie is relatively well defined after 15 years of multidisciplinary efforts. Although the causative mechanism has not yet been fully understood nor quantified, most of the causative elements have certainly been identified. The accurate hypocenters provided by an appropriate seismic network can now be correlated to and contained by a combination of intersecting geological structures. This spatial correlation of structure and seismicity rests on so many converging observations that a cause-and-effect relationship is logically postulated, and accepted by almost everyone.

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EARTHQUAKES ON THE CONTINENTAL MARGIN OF EASTERN CANADA:
NEED FUTURE LARGE EVENTS BE CONFINED TO
THE LOCATIONS OF LARGE HISTORICAL EVENTS?

by

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INTRODUCTION

The continental margin of eastern Canada has experienced two magnitude 7 earthquakes during this century: on the continental slope south of Newfoundland in 1929, and in Baffin Bay in 1933. Regions near these epicenters have experienced continuing earthquakes in the magnitude 5 range. The continental margin off Labrador has also experienced numerous magnitude 5 earthquakes, but no known large events. The seismotectonic setting of the margin is poorly known and no significant geological features have yet been associated with the historical seismicity. The mean recurrence period of the large earthquakes at or near their known locations is believed to be longer than the historical period. The possibility must therefore be considered that similar large earthquakes have occurred elsewhere along the margin in prehistoric times and can occur elsewhere in the future.

SEISMOTECTONICS OF THE EASTERN CANADIAN MARGIN

The continental margin of eastern Canada extends along the continental slope for 5500 km from the Georges Bank and the Scotian Shelf in the south to the northern end of Baffin Bay (Figure 1). The margin was formed in the early stages of rifting between continental masses that separated to form the Atlantic Ocean and the oceanic region between Greenland and Baffin Island. The faults created by rifting and subsidence are now experiencing a compressive tectonic regime with the "push" of the North American plate away from the mid-Atlantic ridge acting against a resisting athenospheric drag

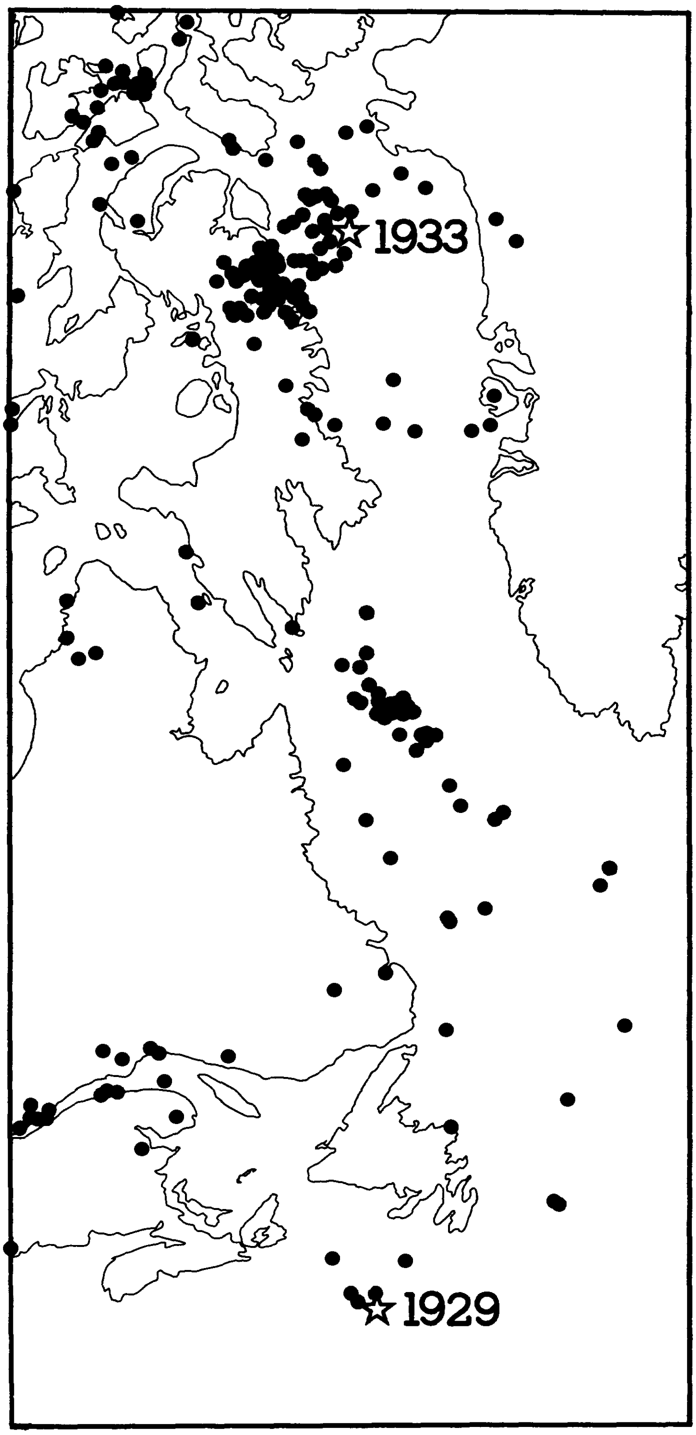

Figure 1. Seismicity of the eastern Canadian continental margin. Shown as dots are all earthquakes from the Canadian Earthquake Epicentre File of magnitude 4 and greater from 1960 to 1980. Shown as stars are the locations of the magnitude 7, 1929 Laurentian Slope and 1933 Baffin Bay earthquakes.

beneath the plate. Additional stresses are produced by on-going postglacial rebound and by the accumulating weight of the thick sedimentary deposits.

It is generally assumed that earthquakes along the margin are occurring in the old rifted continental lithosphere in reaction to the contemporary stress field. Stresses due to glacial unloading have been thought sufficient to reactivate old faults parallel to the margin (Stein et. al., 1979). Other studies have suggested the earthquakes are related to linear features such as fracture zones and seamount chains that are nearly normal to the margin (Sykes, 1978; Stewart and Helmberger, 1981). However, seismological, geological and other geophysical techniques have so far been unable to make a clear association between the seismicity and the structual geology of the margin.

During historic times the earthquake activity has been concentrated on the continental slope at the mouth of the Laurentian Channel, in the Labrador Sea, and in Baffin Bay (Figure 1; see also Basham and Adams (1982) and Basham et al. (1983)). The 1929, magnitude 7.2 earthquake on the Laurentian slope caused the slumping of sediments from a 200-km length of the slope; a turbidity current that broke numerous telegraph cables; and a tsunami that caused the loss of 27 lives in southern Newfoundland (Doxsee, 1948). Relocation studies suggest subsequent seismic activity is concentrated in an east-west zone about 100 km long. Seismic reflection profiling (King, 1979) has located relatively young faulting in the Laurentian Channel, but offsets in the uppermost sediments are not yet proven.

There are reports (Smith, 1962) of felt earthquakes from fishing villages along the Labrador coast as early as 1809. However, there is no evidence from recent instrumental data that significant earthquakes are occurring onshore in this region. The older events likely occurred offshore, where there have been six instrumentally-located earthquakes in the magnitude 5.0-5.6 range, but none larger. These earthquakes are divided into two trends, one along the ocean-continent boundary and another near the Labrador Sea Ridge (Basham and Adams, 1982).

The largest earthquake known to have occurred in northern Canada was magnitude 7.3 in Baffin Bay in 1933. Since then there have been three earthquakes larger than magnitude 6 and numerous smaller events in a poorly defined zone. There is evidence for seafloor spreading in Baffin Bay (Jackson et al., 1979), but the earthquakes are not associated with the extinct spreading centre. They occur inland of the 2000-m isobath in a region of thick sediment accumulation (Wetmiller and Forysth, 1982).

CAN FUTURE EARTHQUAKES OCCUR ANYWHERE ALONG THE MARGIN?

As the seismotectonic models for both the continental margin as a whole, and for the regions of historical earthquake concentration are very poorly defined, evidence must be sought to determine the possibility of future large earthquakes at other locations along the margin. The present evidence is speculative and involves a considerable lack of knowledge about the recurrence intervals of the larger earthquakes and their associated long-term crustal deformations.

In the models of historic seismicity employed for probabilistic seismic risk estimates of the eastern margin for National Building Code applications (Basham et. al., 1982), it is difficult to estimate stable magnitude recurrence relations for source zones that contain only a single large earthquake. For such single events the return period is unknown, but it is believed to be longer than the historical period. This is the case for both the Laurentian Slope and Baffin Bay source zones. The only independent evidence on recurrence intervals is provided by preliminary marine geophysical and sediment sampling experiments in the area of the 1929 Laurentian Slope earthquake (Piper and Normark, 1982). Much of the sediment that slumped in 1929 was originally deposited during the Pleistocene and hence had remained stably on the slope for more than 10,000 years before being shaken loose. This, and the paucity of Holocene turbidites on the deep sea floor, suggest that 1929-sized earthquakes are very infrequent within about 100 km of the 1929 epicentre. If they are infrequent at any one location along the margin, there may have been similar events at other locations in prehistoric times for which no marine geological or continuing seismicity evidence has yet been found.

A model that claims ignorance as to where along the margin the large earthquakes are likely to occur, distributes them equally along the entire 5500-km length of the continental slope (Figure 2). A magnitude recurrence relation for this model (Figure 3) derived from known Laurentian Slope, Labrador Slope and Baffin Bay seismicity seems to provide a reasonably stable estimate of the rate of significant earthquakes. If they are equally likely at any location, the recurrence estimate suggests one earthquake of magnitude 7 or greater per thousand years per thousand kilometers along the slope. This rate is comparable to that suggested by Wentworth and Mergner-Keefer (1981) for the eastern seaboard of the United States. Such earthquakes would significantly shake a 200-500 km lenth of the margin.

If we postulate that each of these large events has a long aftershock sequence, of the order of 100-200 years, i.e., that current seismicity on the Laurentian Slope and in Baffin Bay represents aftershocks of the 1929 and 1933 earthquakes, it is possible that the current Labrador continental slope earthquakes are late aftershocks of a similar large event. Were one or more such events felt in Labrador fishing villages in the early 1800's? Any by extension of the argument, are some of the gaps in contemporary seismicity along the margin the locations of even older events for which the aftershock sequence has died down? These speculations are depicted graphically in Figure 4.

If magnitude 7 and greater earthquakes occur at rates of only 1 per 1000 yr per 1000 km of margin, the long-term deformation rate they represent is quite low, and is far lower than the rates implied were the seismicity concentrated in a few discrete zones. Assuming pure reverse faulting and using the method of Hyndman and Weichert (1983), this occurrence rate represents about 0.04 mm per year of shortening across the margin along its entire 5500-km length. Such a rate does not seem unduly high for a passive margin since on geological time scales it is equivalent to 40 m of shortening in the last million years. As the shortening can occur on any of many parallel rift faults, the movement on each need by only a few m per million years.

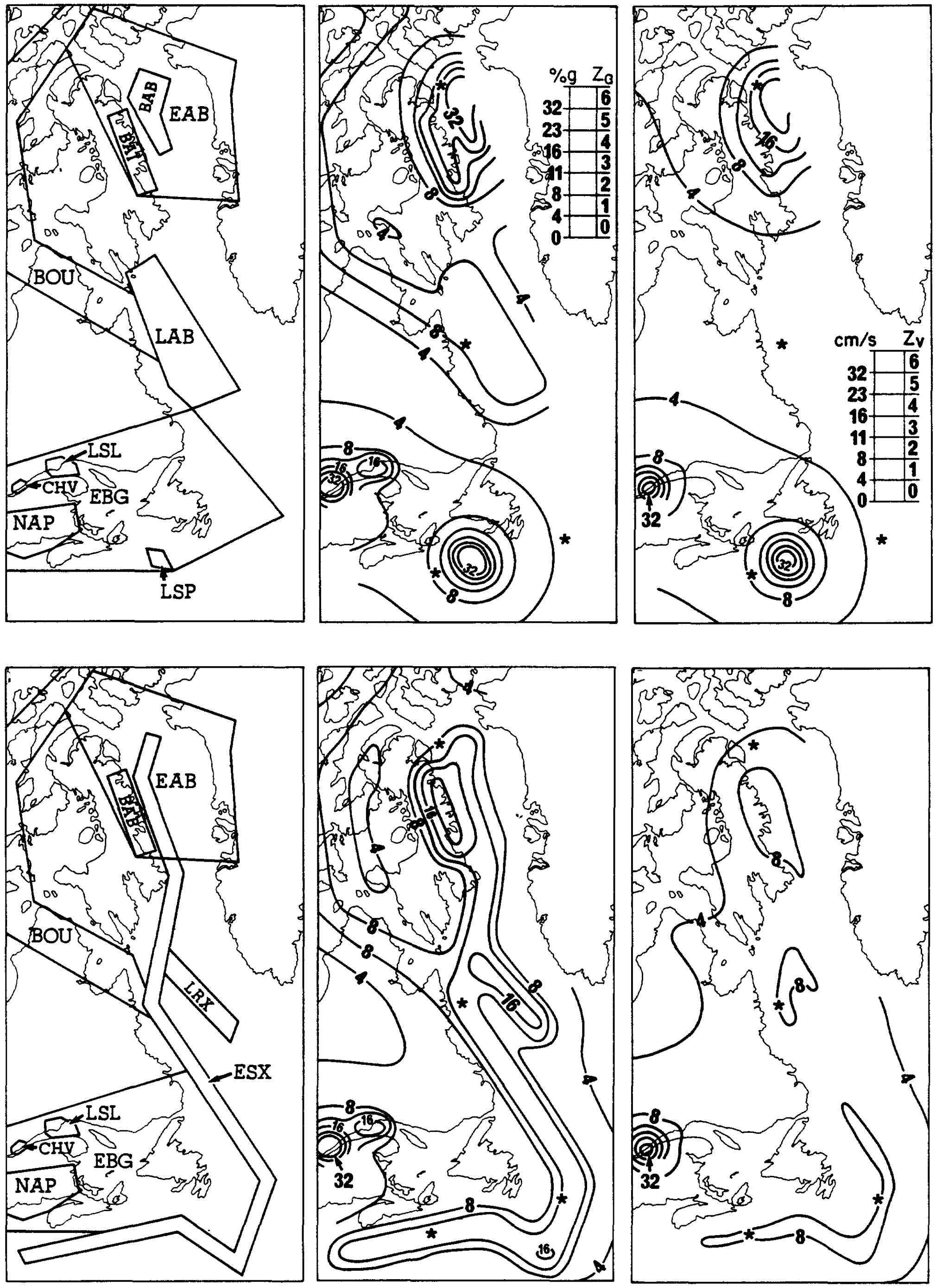

Figure 2. Earthquake source models and computed peak horizontal acceleration and peak horizontal velocity with a probability of exceedence of 10 percent in 50 years. Upper: the eastern margin portion of the national source zone model and acceleration and velocity zoning maps adopted for National Building Code applications (adapted from Basham et. al., 1982). Lower: Speculative alternative model for offshore seismicity which assumes that future large earthquakes are equally likely at any location along the margin (ESX), and resulting acceleration and velocity contours (adapted from Basham et. al. (1983).

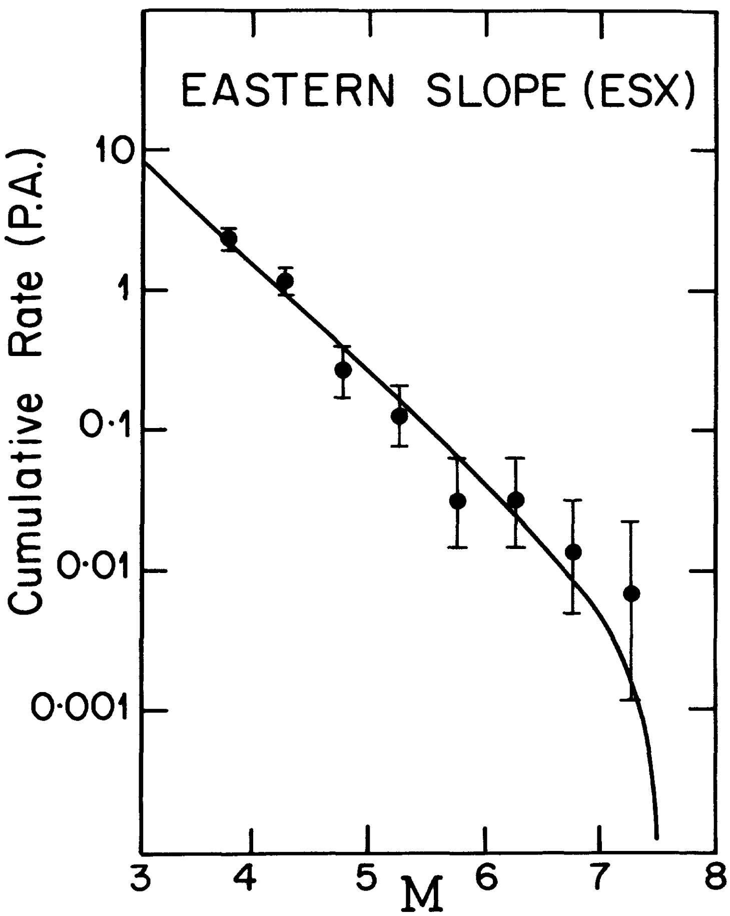

Figure 3. Cumulative magnitude recurrence relation for the ESX source zone (Figure 2, lower left) developed by combining the historical seismicity of the Laurentian Slope (LSP), Baffin Bay (BAB) and the continental slope portion of the Labrador Sea (LAB) source zones (Figure 2, upper left).

IMPLICATIONS FOR EARTHQUAKE RISK

The historical seismicity of the eastern Canadian continental margin has been modelled as part of the national earthquake source model to estimate probabilistic peak horizontal acceleration and velocity zoning maps for National Building Code applications (Basham et. al., 1982). The Building Code applies primarily to common buildings on land, and it is found that the risk estimates for this purpose are not strongly affected by alternative models of the eastern offshore seismicity. However, estimates of earthquake risk at offshore sites are strongly affected by assumptions about the locations and rates of future large earthquakes.

Comparisons of the probabilistic seismic ground motion on the Building Code zoning maps and that produced by a model that assumes the large earthquakes are distributed uniformly along the continental slope shows 2- to 4- fold differences in regions of current or potential petroleum exploration on the continental shelf (Figure 2). However, this model also suggests that large earthquakes will occur only very infrequently beneath a particular location on the continental margin.

A further development of the uniform-distribution model would include the concept of seismic gaps for earthquake risk analysis, i.e., that locations of recent large earthquakes are regions least likely to experience a large earthquake in the near future; whereas in the quiescent zones a large earthquake may be imminent (Figure 4). However, the risk model must also account for continuing activity, at least to the magnitude 6 level, in regions like the Laurentian Slope, Labrador Slope and Baffin Bay that are experiencing current activity. This concept must be very well developed to be useable. In the meantime the perceptions of earthquake risk on the part of the public, the proponents of industrial facilities, and the regulators alike will not allow the largest and most recent earthquakes to be ignored in the siting and design of important facilities.

The hypothesis of uniform distribution of large earthquakes along the eastern Canadian continental margin over long periods of time may well be incorrect.

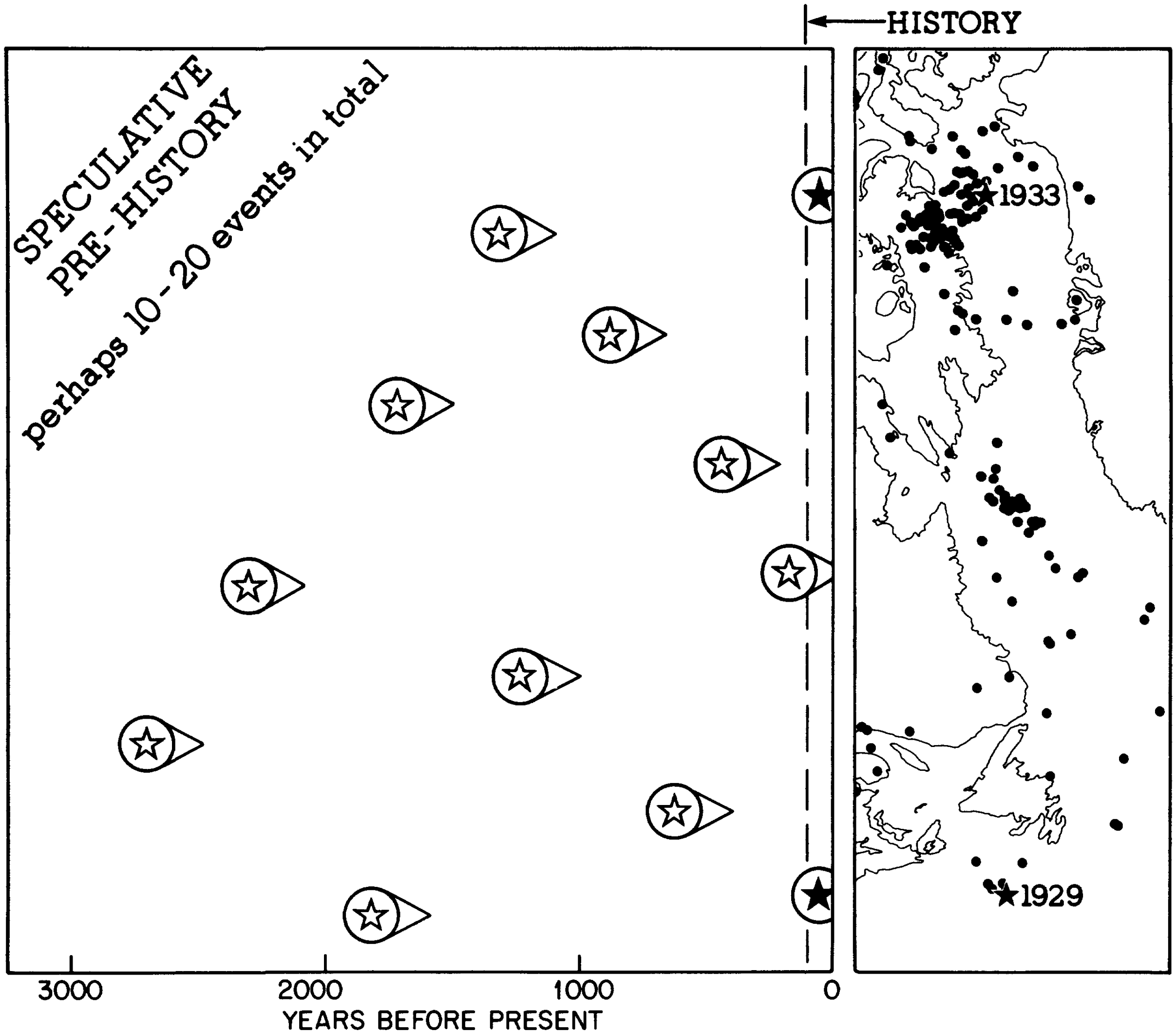

Figure 4. Seismicity of the eastern Canadian margin (right; from Figure 1); and speculative history and pre-history of significant earthquakes, with aftershock tails (left). This speculative model assumes that magnitude 7 and greater earthquakes on the continental margin sufficiently perturb the local stress regime that continuing activity for a period of 100-200 years can be considered as long aftershock sequences.

Research on the seismotectonics of this region must be directed toward testing and refining this and other alternative models.

FUTURE RESEARCH

Directions of future research, some of which are underway or being planned by the Department of Energy, Mines and Resources, but all of which we urge other agencies to consider, include the following:

1) Improved land-based monitoring of the eastern margin to ensure complete coverage at the magnitude 3 level in order to delineant active and inactive segments of the margin.

2) Ocean-bottom seismograph experiments at selected sites to define the detailed distribution and nature of detected seismicity.

3) High-resolution seismic profiling, including the analysis of industry data, to search for recent and deep-seated faults.

4) Side-scan mapping and sediment sampling to establish the nature of historic and prehistoric instabilities on the sea bottom.

5) Determination of the deep structure of the continental shelf and margin to provide a structural setting for earthquake interpretations.

6) Focal mechanism and stress studies for development of seismotectonic models.

7) Relocation analysis of historical earthquakes and search for written evidence of pre-instrumental significant earthquakes.

8) Extension of general concepts to the eastern U.S. continental margin and comparison of results with other passive margins worldwide.

Of particular importance will be research that leads to a better understanding of why the large earthquakes on the eastern Canadian margin have occurred near the continental slope, whereas the 1886 Charleston earthquake and perhaps the

1755 Cape Ann earthquake occurred at, or very near the coast of the Eastern United States.

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Contribution from the Earth Physics Branch No. 1063.

NUCLEAR REGULATORY COMMISSION'S RESEARCH PLANS FOR THE FUTURE

by

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"Research Plans for the Future" is a very broad topic. In this abstract it is addressed from the perspective of a mission-oriented Federal agency with specific regulatory responsibilities. The Nuclear Regulatory Commision is required by law to regulate the manufacture, storage, use, and disposal of nuclear materials so as to protect the public health and safety. Thus, the NRC's interest in the Charleston, South Carolina, earthquake problem is not primarily to advance science but rather to investigate and understand the potential impact of a resolution of the problem on public health and safety.

The Earth Sciences Branch (ESB), developed a Seismotectonic Research Plan (April 19, 1982 memo from Arsenault to Minogue) establishing a research program for Fiscal Year (FY) 1982 through FY 1985. The Plan is currently being revised to reflect the advancing state-of-knowledge, changing regulatory needs, and budgetary priorities.

The original Seismotectonic Plan addressed the NRC's needs for geoscientific research in support of nuclear power plant licensing actions and in development of regulation and regulatory guidance. The November 18, 1982, U.S. Geological Survey (USGS) clarification of its position on the Charleston earthquake helped launch this workshop which is providing a stimulus for the revised Plan. The basic thrust of the Plan is not expected to be greatly altered by the new USGS position but a number of details are being retuned to better assimilate current hypotheses concerning Eastern United States seismicity. In part, the Plan cannot be greatly redirected because it covers and must continue to cover the Eastern United States in a balanced fashion. This balance is derived from the real and perceived seismic risks and these risks have not changed significantly since the original Plan was laid out.

Table 1 is a copy of the ESB budget for FY 1983. It is broken down into Regional Programs and Topical Programs. The Regional budget figures provide an indication of the priority and balance achieved in the ESB program based on uncertainty in seismic hazard assessment and the number of nuclear power facilities in the different regions.

One of the principal objectives sought by the NRC staff at this workshop is the development of a sense of closure or direction for the research program in the Charleston area. We were interested in the development of a sentiment, if not a consensus, among the knowledgable investigators of what experiments are critical for resolution of the apparently expensive Charleston problem. This closure must be thoroughly based in good science. A synthetic or imposed sense of closure would be too misleading and counterproductive to be tolerated.

By the end of the workshop such a consensus about important experiments or data collection seemed to be developing from the users of the seismographic network data. From the geophysicists and geologists a consensus was developing. For additional seismic profiling lines (no apparent consensus on locations) and for paleoseismicity and geomorphologic studies (paleolique-faction and ground radar studies appeared as leading geologic contenders).

This apparent development of some consensus does not ameliorate the perceived lack of coordination among the principal investigators and the previous failure to define a program of research to efficiently integrate the available data and personnel both within the government and outside.

TABLE 1

EARTH SCIENCES BRANCH-Research

FY 1983 BUDGET

GEOLOGY AND SEISMOLOGY

REGIONAL STUDIES

Southeastern U.S. (excluding Charleston)	722
Charleston	650
Northeastern U.S.	1200
New Madrid Region (plus Anna Ohio)	560
Nemaha Ridge	120
Pacific Northwest	30

TOPICAL STUDIES

Site Specific Spectra	100
Probabilistic Studies SSE	150
Seismic Analysis and Strong Motion Instrumentation	325
USGS Topical Studies	460
Geotechnical Engineering	100

PLANS AND PROGRAMS OF THE U.S. GEOLOGICAL SURVEY FOR STUDYING EASTERN SEISMICITY

by

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INTRODUCTION

The U.S. Geological Survey (USGS) participates in the National Earthquake Hazards Reduction Program with the Federal Emergency Management Agency (FEMA), National Science Foundation (NSF), and National Bureau of Standard (NBS). The Survey's national program has five elements:

1) Regional Monitoring and Earthquake Potential Studies: Seismological and geological analyses of the current seismic activity, active geologic faults, and earthquake potential of all seismic regions in the United States.

2) Earthquake Prediction Research: Laboratory and theoretical studies and field experiments in some areas identified in monitoring with the goal of establishing the procedures and knowledge needed in reliable prediction of the time, place, and magnitude of damaging earthquakes.

3) Evaluation of Regional and Urban Earthquake Hazards: Evaluation of the earthquake hazards of ground shaking, surface faulting, ground failure, and tectonic deformation in earthquake-prone urban areas. Research includes the demonstration of specific methodologies

tailored for use in each region and activities to foster implementation of loss-reduction measures in the urban area at risk. The program element does not include microzoning or site-specific studies. At the present time, studies are being conducted in the following urban areas: 1) Wasatch front, Utah, 2) southern California, 3) northern California, 4) Anchorage, Alaska, 5) Puget Sound area, Washington, 6) Mississippi valley, 7) Charleston, South Carolina, 8) Boston, Massachusetts, and 9) Buffalo-Rochester area, New York. This program element will be described in more detail later in this paper.

4) Data and Information Services: Information on earthquake occurrence is providing for use by the public, other Federal agencies, State and local governments, emergency response organizations, and the scientific community.

5) Engineering Seismology: Analyses of data on strong earthquake ground motion, the results of which are provided to other Federal agencies and the engineering community for establishing criteria for the earthquake-resistant design and construction of buildings, hospitals, dams, nuclear power plants, and other facilities.

The USGS funds research by the scientific and engineering community through a program of grants and contracts with universities, private companies, and agencies of State, regional, and local governments, issuing a request for proposals annually in December to encourage participation. All regions of the United States have participated in the grants and contracts program which receives about 25 percent of the funding allocated to the Survey's Earthquake Hazards Reduction Program.

RESEARCH ON EASTERN SEISMICITY

Since 1977, the USGS has conducted research on Eastern seismicity as part of the National Earthquake Hazards Reduction Program. In addition, other programs such as the U.S. Geological Survey's Structural Framework Program and the Nuclear Regulatory Commission's Seismotectonic Program have provided support. The Survey's level of effort in the Eastern United States is about 20 percent of the level of efforts of its national program.

The USGS is currently reviewing its research program on eastern seismicity, seeking to establish an integrated research program that focuses on scientific issues whose resolution will contribute to a better understanding of eastern seismicity. These issues are outlined below:

<u>Issue 1</u>: What is the relationship between the historic earthquake record, preexisting structures and earthquake potential?

A. What is the contemporary distribution of seismicity?

1. What part of the crust is seismogenic, and what is its physical character?
2. What are the physical characteristics of eastern earthquakes?

B. Is there a relationship between small and large earthquakes in intraplate environments?

1. Spatial and temporal relationships?
2. Source parameter relationships?

C. What is the recurrence behavior of intraplate earthquakes?

1. Is there evidence of progressive deformation?
2. Have any events had a recurrence?

D. What is the association between earthquakes and geologic features?

1. At specific locations, is there a systematic relationship between equation hypocenters, their focal mechanisms, and geologic structures?
2. What is the crustal structure of seismically active and inactive regions?
3. Are their identifiable sets of specific seismogenic structures.

<u>Issue 2:</u> What is the relationship between the state of stress, rate of deformation, and earthquake potential?

A. What is the rate of contemporary crustal deformation?

1. Is the rate of crustal deformation spatially uniform in the Eastern and Central United States?
2. Is there a correlation between contemporary crustal deformation and the geologic and seismogenic record?

B. What is the distribution of crustal stresses?

1. Is there an atlantic Coast Stress Province, and what is its orgin?
2. Is the stress field in areas of large eastern earthquakes (e.g., New Madrid and Charleston) similar or different from that in the surrounding areas?
3. How does the pattern of crustal stress correlate with crustal structure, geology, and contemporary strain?

C. What is the long-term rate of deformation as indicated in the geologic record?

1. What part of the crust is seismogenic and what is its physical character?
2. What are the physical characteristics of eastern earthquakes?

Issue 3: What is the relationship between the strong ground motions recorded in the Western United States and those which may be expected in the Eastern United States?

A. Are there significant differences in source characteristics of earthquakes in the Eastern United States.

1. What is the average stress drop expected for these earthquakes?
2. What is the appropriate scaling of source and ground motion characteristics with magnitudes?

B. What are the source dynamics of seismogenic failure in the Eastern United States?

1. What does the combination of source mechanisms, and locations imply about nature for crustal stresses in the Eastern United States?
2. Can source parameters and source mechanism studies be utilized to predict seismogenic failure on a larger scale?

C. How does the marked difference between the geology and tectonics of the Eastern and Western United States affect the expected strong ground motion?

1. What are the appropriate attenuation relations for peak acceleration, peak velocity, etc.?
2. What properties of the Lg waveguide are relevant to predicting damaging strong ground motion?
3. Can high-frequency site response be predicted from a knowledge of the near surface velocity structure at the site?

Issue 4: How do earthquake effects correlate with local geology?

Issue 5: Can probabilistic procedures be used to model realistically the earthquake ground-shaking hazard in the East?

An integrated research program offers the promise of substantially advancing the state-of-knowledge on eastern seismicity.

COMPONENTS OF THE REGIONAL AND URBAN HAZARDS PROGRAM ELEMENT

Beginning October 1, 1983, The U.S. Geological Survey (USGS) will initiate the new program element, "Evaluation of Regional and Urban Earthquake Hazards." This element, a part of the National Earthquake Hazards Reduction Program (NEHRP), was created to develop the basic information and the partnerships needed for evaluating earthquake hazards and assessing the risk in broad geographic regions containing important urban areas and to provide a basis for loss-reduction measures that can be implemented by local governments. The goal is to provide an integrated program having comprehensive research goals and producing generic information that can be used to reduce earthquake losses in urban areas. The scientific emphasis is on developing a fundamental physical understanding of the cause, frequency of occurrence, and the physical effects of earthquake ground shaking, surface faulting, ground failure, and tectonic deformation in various geographic regions. This element requires a high degree of team work, utilizing a multidisclipinary Task Force to accomplish the goals of each task. Users of the information produced by this program (for example: agencies of Federal, State, and local government involved in emergency response, building safety, and planning) cannot find such an integrated synthesis and evaluation of earthquake hazards in the scientific literature. Also, loss estimates have not been updated in most urban areas for many years and the risk may be seriously underestimated due to the sharp increase in building wealth and construction.

The tasks of the program element are described below:

Task 1: Information Systems - Because each research project produces basic data and information, the goal is to produce a comprehensive information system, available to both internal and external users, designed to give a data base that is as uniform in quality and as complete on a regional and urban scale as possible. Several categories of data can be identified, including: seismicity, gravity and magnetics, well logs, seismotectonic data, fault trenching data, stress measurements, seismic reflection profiles, ground failure data, soils data, ground motion data, inventory of structures, damage assessments, bibliographic references, publications, and maps. Because of the potentially large scope of the task, care must be exercised to create a system that is both pratical and economical.

Task 2: Hazards Evaluations and Synthesis - The goal is to produce synthesis reports describing the state-of-knowledge about earthquake hazards (ground shaking, surface faulting, earthquake-induced ground failures, and tectonic deformation) in the region and recommending future research to increase the state-of-knowledge required for the development and implementation of loss-reduction measures. The research will provide a fundamental understanding of the nature and extent of the earthquake hazards. Development of models (hypotheses) and analysis of data are important aspects of this task.

Task 3: Ground Motion Modeling - The goal is to develop deterministic and probabilistic ground motion models and maps. Commentaries will be provided so that others can use the models for generating ground-shaking hazard maps and for evaluating the sensitivity of uncertainity in median values of important physical parameters.

Task 4: Loss Estimation Models - The goal is to develop economical methods for acquiring inventories of structures and developing a standard model for loss estimation. Commentaries on the use of such a model and its limitations will be provided so that others can use it. Loss estimates will be produced.

Task 5: Implementation - The goal is to foster implementation of loss-reduction measures in the urban area. In an urban area, the severity of an earthquake disaster depends upon three factors. They are:

1. The magnitude of the earthquake--the larger the magnitude the greater the potential for severe levels of ground shaking and other earthquake effects.

2. The location of the earthquake source relative to an urban area--the closer the source of energy release to an urban area the greater the potential for damage.

3. The degree of earthquake preparedness within the urban area--the lower the level of preparedness the greater the potential for disasterous consequences in an earthquake.

The earthquake that devastated the city of Tangshan, China, on July 28, 1976, is one example of an extreme earthquake disaster. This industrialized city of approximately one million people was located in a seismic zone, according to the Chinese building code, which did not require earthquake-resistant design. Therefore, this city of unreinforced brick buildings was almost totally unprepared for the magnitude 7.8 earthquake which epicenter was within the city and which fault rupture extended beyound its borders. The result was a very great disaster. Eighty-five precent of the city's buildings collapsed or were severely damaged, and several hundred thousand people lost their lives. Industries in Tangshan were out of operation for long periods, and it took more than 6 years for one-half to the city to be rebuilt.

To increase the state-of-preparedness in an urban area, conferences and workshops will be convened to bring together producers and users of earthquake hazards information. Participants representing business and industry, the private sector, and Federal, State, and local government will be involved in the conferences and workshops. Proceedings of the conferences and workshops will be disseminated to a wide audience, promulgating the research results and recommending actions, based on these results, that will increase the state-of-preparedness.

The scientific and engineering community will be invited to participate in this program element through the Survey's programs of grants and contracts.

NATIONAL SCIENCE FOUNDATION'S EARTHQUAKE HAZARDS REDUCTION RESEARCH PROGRAM

National Science Foundation (NSF) supports fundamental research studies on earthquakes and basic and applied research on earthquake engineering and policy. Through its studies of seismology, gravity, geodesy, magnetism, Earth currents, heat flow, and the behavior of natural materials at high pressure and temperatures, NSF's Earth Sciences Division improves the understanding of the natural phenomena involved in an earthquake and provides knowledge necessary for the potential prediction of earthquakes and destructive ground motion. The Division of Civil and Environmental Engineering supports research in the fields of earthquake engineering, architecture, urban planning, and societal response in order to obtain needed information on the nature and effects of destructive ground shaking as well as on practical methods of analysis, design, and planning for safe and economical earthquake countermeasures for both existing and planned structures. Through its Societal Response Program, NSF supports research on the responses of individuals, organizations, and communities to earthquakes and related hazards, which are critical to emergency response planning and mitigation, particularly in the case of a long-term prediction. Thus, the Societal Response Program provides information on the socioeconomic aspects of hazard mitigation; a data base for hazard preparedness planning; a greater understanding of disaster impacts, responses, and recovery; and a basis for improving the dissemination and utilization of earthquake hazard information by decision-makers and the public.

NSF funds unsolicited proposals to conduct its research program. All regions of the United States have participated in the program.

FEDERAL EMERGENCY MANAGEMENT AGENCY'S PLANS FOR THE CHARLESTON, SOUTH CAROLINA, AREA

by

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INTRODUCTION

During the past three days we have participated in an intense and interesting series of discussions on the seismicity of the Charleston area and its surroundings. The lack of a preponderant hypothesis on the cause of such seismicity, however, does not mean that we should slacken the pace of earthquake preparedness for the area. Quite the contrary. The fact remains that a damaging earthquake has occurred in this area in 1886 with substantial loss of life and property and another can occur any time. The need for earthquake preparedness, therefore, remains, and my remarks will cover the Federal Emergency Management Agency's (FEMA) plans to strengthen this preparedness.

FEMA EARTHQUAKE-RELATED ACTIVITIES

FEMA is supporting two types of earthquake-related activities that are relevant to the Charleston area, one that is general in nature and another that is site-specific.

(1) Activities of a General Nature

FEMA is funding an effort that will produce, in about a year, a resource document on improved seismic building practices. Based on a considerable body of earthquake engineering knowledge (developed mainly under National Science Foundation sponsorship), the Applied Technology Council (ATC) compiled a set of seismic building provisions in 1978. In 1982 FEMA funded the Building Seismic Safety

Council of the National Institute of Building Sciences to assess these provisions through a series of trial designs. About 50 buildings of different size, configuration, construction, and occupancy and located in nine cities (one of which is Charleston) are being designed first according to existing local codes and then according to the ATC provisions. The objectives of this effort are to estimate the economic and social impact of the use of these provisions; evaluate their usability by designers, builders, and building regulatory officials; establish their technical validity; and produce objective information as to the transferability of the provisions to other locations. Once the results of this effort are compiled and assessed and adapted to local needs, a basis will exist for undertaking an evaluation of construction codes, standards, and practices in each area to improve the seismic resistivity of new buildings. A comparable undertaking in regard to existing hazardous buildings and both new and existing lifeliness are planned for the future. The results of these efforts will eventually form the basis for earthquake mitigation in the building industry in the Charleston area.

An effort is also underway to develop uniform seismic standards for Federal buildings and a set is already in existence, but not yet uniformly applied. In the meantime, several agencies, notably the Department of Defense, the Veterans Administration, and the Department of Housing and Urban Development are applying their standards and practices.

Parallel with these activities, we plan to continue the ongoing activities to increase hazard awareness and educate the general public and specific audiences about the consequences of an earthquake. In this regard, in addition to support for this workshop, FEMA will soon fund an earthquake education center at a well-established and recognized institution in this area to serve as a repository of basic earthquake-related documentation and to foster general information transfer.

(2) Site-Specific Activities

Site-specific activities for this area were started at a workshop similar to this one held in Knoxville, Tennessee, in September 1981. A few individuals of who Harry Lambright, in a earlier session, identified as "earthquake enterpreneurs" formed the South Carolina Seismic Safety Consortium at that workshop. The Consortium in 1982, initiated a study of the vulnerability to earthquake hazards of this area, using a small amount of FEMA and USGS funding and a great deal of local voluntary talent and work. This effort is continuing today. FY 84 resources, unfortunately, will not be sufficient to expand it as it should be expanded. Consequently, in FY 84 it should be concentrated on two activities: (1) a concerted planning effort, utilizing all major segments of the private and public sectors in the area, to lay out in detail a well-thoughtout and well-articulated 3-5 year plan for preparing for, responding to, and recovering from seismic hazards in Charleston and other affected areas.

This broader multi-year effort (that could start in FY 85) should include the determination of:

(1) the exact geographic areas to be covered, in addition to Charleston, based on the best geotechnical information available at that time;

(2) the physical damage to structures from not only ground shaking, but also other earthquake-related phenomena, like soil failures. Principal emphasis should be placed on: high-occupancy buildings; facilities required for response operations; and processess capable of creating secondary hazards (e.g. toxic spills);

(3) number and kind of casualties that could be expected at different times of the day and different times of the year; and

(4) special problems created by the nature of the hazard or the physical environment (e.g. how to deal with the major population concentration on the peninsula in the immediate hours after an earthquake, if it were to become isolated as a result of serious damage to highways and bridges.)

The results of this multi-year effort will provide the basis for two additional activities of a complementary nature:

(1) actions for abating the earthquake hazards in the short- and long-range, including: strengthening of vulnerable lifelines and supporting facilities; strengthening of existing structures (in this regard those with high occupancy and significant response roles need priority attention); limiting further development on hazardous soils or requiring special construction provisions; developing, adopting, and enforcing improved seismic construction practices; and making provisions for handling the large number of treasured historical monuments and homes located in this area; and

(2) the preparation by State and local officials of detailed plans to respond to a large-magnitude earthquake in the area (e.g. a repetition of the 1886 earthquake.)

ACTIVITIES RELATED TO OTHER HAZARDS

For hurricanes, maps and charts showing possible inundation area and wind speeds are being prepared in FY 83, using a large number of simulation runs of a mathematical model (SLOSH). For FY 84, this information will be used as a basis for a vulnerability analysis of the Charleston and surrounding areas. The emphasis will be on preparedness actions needed to save lives. Evacuation routes, therefore, will be identified, with special emphasis on barrier islands and other coastal areas; safe shelters for caring and feeding of evacuees (and later homeless) surveyed and identified (or revalidated); warning and communications procedures established or reaffirmed; and an estimate of casualties and homeless made.

In subsequent years, other aspects of hurricane preparedness will be emphasized, including activities to save property in the long term, such as land-use planning, and improvement and enforcement of building codes for protection against both water and wind loads. The major portion of this effort is expected to be completed by FY 87, by which time hurricane preparedness should have become part of State and local institutions of government, with a minimum of Federal maintenance support. A new flood plain map of the area is also in preparation.

CONCLUDING REMARKS

There are other hazards in this area that also need to be considered: very substantial national security installations, nuclear power plants, industrial installations using toxics in their processes, and dams. There, therefore, appears to be an ideal subject of a multihazard approach. The plans of various Federal agencies are being presented in this session. A multihazard approach requires that the common elements, and unique features, and resources of all these activities be identified and then systematically harnessed. How to do it in an effective and integrated manner, and the tapping of private sector energies and means, and the necessary institutional arrangements to bring it about are the challenges of hazards planning in the Charleston area and, indeed, in the whole United States. I urge you to accept these challenges and help in overcoming them, as you conduct your day-to-day activities in the coming months.

CORPS OF ENGINEER'S COMMENTS ON THE POTENTIAL FOR A CHARLESTON, SOUTH CAROLINA, EARTHQUAKE

by

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The following are comments of the author who participated in the Charleston Workshop of May 23-26, 1983. The Corps of Engineers has never taken an official position in this matter.

The U.S. Geological Survey has taken a position that a Charleston-type earthquake ($M = 7.0$, $I_o = XI$) could conceivably occur anywhere in the Eastern Seaboard of the United States.

The principal theories concerning the causes of seismicity in the Eastern United States are:

1) Focusing of regional stresses at heterogeneities (plutons or other features) in the subsurface and release of these stresses along associated faults.

2) Possible small-scale introduction of magmatic material into the plutons at depth with an accompanying buildup of stresses.

3) Focusing and release of regional stresses along structural trends, such as Boston-Ottawa, Charleston-New Madrid, etc. These trends are interpreted as Mesozoic rifts with magmatic intrusions and likely to be zones of weakness, The postulated rifts do not show up in any pronounced way in the magnetic and gravity maps as do other structural features with totally different orientations.

4) Slow regional compression causing activation of preexisting regional overthrusts (Wentworth and Mergner-Keefer). Such activation should

show up in the form of developing seismicity. No such premonitory events have been observed.

5) Extensional movement (sagging Atlantic Coast in New England) which activates irregularities in the coastline, principally where major grabens intersect the downwarping. Inland, these forces may cause activation of faults with northwesterly and northerly orientations (Barosh).

The Wentworth and Mergner-Keefer hypothesis, and that of the Mesozoic rifts, suggest that a major earthquake could happen where none has happened before. The evidence for this possibility is not very convincing. To accept such a possibility should require some additional evidence. Data presented at the meeting showed that every large intraplate earthquake in the world (Meckering, New Madrid, the St. Lawrence Valley, Koyna, etc.) had associated seismicity, so that, if the large earthquakes had not happened, there would be reason to expect them to happen.

The evidence presented at this meeting suggests that there is no valid basis for moving the Charleston earthquake.

TENNESSEE VALLEY AUTHORITY'S SEISMIC MONITORING PROGRAM

by

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INTRODUCTION

In an effort to more fully assess the seismicity of our region, the Tennessee Valley Authority (TVA) has initiated a seismic monitoring program. This program is a cooperative effort with the regional observatories at Virginia Polytechnic Institute and State University, Georgia Institute of Technology, Memphis State University, and the University of Kentucky. A supplementary regional array, strong-motion instrumentation, portable instruments for aftershock monitoring, and the takeover of the four instrument station at Oak Ridge, Tennessee comprise the instrumentation plans of our program. Additionally, as part of our cooperative effort with the regional observatories, TVA will fund a portion of graduate studies at the universities, will provide logistical assistance in installation and maintenance of stations under the observatories operation, will provide monetary and logistical support for aftershock monitoring within the region, and will participate in and encourage a free exchange of data.

INSTRUMENTATION

- Short Period - When installation is completed, a network which will consist of 18 short period vertical seismometers will be located in portions of the region void of present or planned instrumentation.

  Central and northeast Tennessee, north Alabama, and southern Kentucky are the areas of interest, with the goal of this instrument siting being to develop a uniform regional coverage by filling in the voids between networks presently operated by other observatories. Data from these stations will be recorded on develocorders in Knoxville.

- Oak Ridge - TVA has taken over operation of the seismic station that has been operated on the Oak Ridge reservation by the Oak Ridge National Laboratory since the late 1960's. The seismometer array consisting of two short-period horizontals, a short-period vertical, and a long-period vertical will remain on the reservation with the signals being telemetered to Knoxville where they are recorded on helicorders.

- Portable Instruments - Five MEQ-800 seismographs have been acquired by TVA and stationed in Knoxville for temporary deployment during aftershock studies, background noise surveys, and other specialized studies. These instruments were deployed September 24, 1982 and July 8, 1983 for aftershock studies of felt events in the Maryville, Tennessee area.

- Strong-motion - In addition to the instrumentation TVA has installed at its nuclear plants, we have additionally installed strong-motion equipment at two of our fossil plants in west Tennessee and west Kentucky. We also plan on installing strongmotion equipment in either Giles County, Virginia or the Maryville area of east Tennessee. At the selected location we intend to install sensors both on soil and in a borehole in rock to evaluate the differences in ground motion on thin soil versus rock.

COOPERATIVE ARRANGEMENTS

- TVA has made available office space in Knoxville to the eastern representative of the Tennessee Earthquake Information Center.

- TVA has advanced $7800 annually to each of the four area observatories to be used toward graduate funding in the study of seismology. In exchange,the assigned student serves as a point-of-contact for TVA information requests to the observatory.

- TVA has allowed the temporary loan of equipment such as MEQ-800's or our gravimeter for specialized studies relating to the seismicity of the TVA region.

- TVA provides logistical assistance, on request, in the installation and maintenance of seismic stations under the operation of the area observatiories.

- TVA has arranged for a standing fund to be used for per diem and mileage expenses incurred by the area observatories during aftershock studies on earthquakes of interest to TVA.

- All data recorded by TVA's instrumentation is available upon request and is readily being exchanged between TVA and the four cooperating observatories. Interested users should contact:

Bruce Schechter	615-632-4777
Rich Hopkins	615-632-2728
Bill Seay	615-632-4779

TVA's program is basically a research project and is not tied to the licensing or operation of any facilities. Our area of interest in this monitoring is the entire TVA region exclusive of New Madrid. Additionally, seismically active areas such as Giles County, Virginia that lie in "tectonic provinces" that extend into the TVA region are of interest to us.

We are not openly soliciting proposals, but readily offer our available data and assistance. Call us.

ELECTRIC POWER RESEARCH INSTITUTE'S PROGRAM TO ADDRESS SEISMIC HAZARD EVALUATIONS FOR NUCLEAR ELECTRIC GENERATING PLANTS IN THE EASTERN UNITED STATES

INTRODUCTION

The Electric Power Research Institute (EPRI) plans to undertake a program in 1983-1984 to address seismic hazard evaluations for nuclear electric generating plants in the Eastern United States. This program is proposed as the utility industry response to the recent change in position taken by the Nuclear Regulatory Commission (NRC) and the U.S. Geological Survey (USGS), acting as advisor to NRC, regarding considerations of large earthquakes for seismic design evaluations of nuclear electric generating plants in the Eastern United States.

In response to this change in licensing position, the NRC has embarked on an extensive program of investigations. The first part of the NRC program involves a probabilistic assessment of the seismic design basis levels at nuclear plant sites in the East. This effort will utilize the methodology developed by Lawrence Livermore National Laboratory (LLNL) as part of the NRC's Systematic Evaluation Program (SEP). The computations are intended to provide a basis for evaluating the relative levels of seismic hazard at Eastern United States nuclear plant sites and for identifying sites that require further evaluation. The second part of the NRC program involves investigations of tectonic structures and areas that are believed key to understanding the causal mechanisms of large earthquakes in the East.

Editor's Note: Ian Wall, Electric Power Research Institute, presented information on a comprehensive new program to address seismic hazard evaluations for nuclear electric generating plants in the Eastern United States. A manuscript was not available for the proceedings. Because of the interest in this proposed new program, the following information was compiled for the proceedings. Interested readers should contact Mr. Ian Wall or Dr. Carl Stepp, EPRI.

The EPRI program described below addresses Part I of the NRC program. It will supplement the NRC program in two areas:

1) The evaluation of tectonic models (hypotheses) for causes of earthquakes.

2) The aggregation of the tectonic models for seismic hazard analysis.

Significant improvements over the SEP methodology for evaluating seismic sources could be realized through the evaluation of tectonic models (hypotheses) by use of a uniform geologic, geophysical, and seismological data base to form a consistent physical basis for identifying seismic sources.

PROGRAM OBJECTIVE

The program objective is to place the utility industry in a scientifically strong position to respond to any positions taken by the NRC as a result of the Agency's change in position regarding assessment of large earthquakes in the East. The objective will be accomplished through developing a scientifically supported seismic hazard methodology, basic data set, and seismic source models for consistent assessment of regional seismic hazard and a comparative evaluation of the impact of the NRC's change of position.

Specific components of the objective include:

1) Strengthening the seismic hazard methodology.

2) Considering a comprehensive set of tectonic models (hypotheses) for geologic causes of large earthquakes in the East and developing the specific application and physical meaning of each for earthquake generation.

3) Compiling from existing sources a data base for use in evaluating tectonic models, a tectonic framework, and specific seismic sources.

4) Providing major technical input to the NRC's comparative evaluation of seismic hazard at existing nuclear plant sites.

5) Generating broadly based scientific support for the program results.

6) Working closely with the NRC/LLNL program.

7) Identifying additional actions and investigations that could significantly strengthen confidence in the program results and reduce overall uncertainty.

PROGRAM SCOPE

Major activities to be accomplished in the program are:

1) Development of a seismic hazard assessment methodology and its application. This activity includes:

   A) determining the appropriate probabilistic seismic modeling methodology.

   B) establishing appropriate aggregation and weighting of seismic sources, and

   C) compuations of seismic hazard.

2) Tectonic evaluations of the causes of large earthquakes in the Eastern United States. This activity includes:

   A) comprehensive development and evaluation of tectonic models for cause of events,

   B) specific testing of the potentially causative models to establish the physical meaning and specific application of each as an earthquake generating model,

C) combining the tectonic models and specific tectonic features to form a tectonic framework of the East,

D) identification of seismic sources and evaluation of weights based on the tectonic framework and

E) evaluation and weighting of seismicity parameters for use in the seismic hazard computations.

3) Compilation, organization and management of a scientific data base appropriate for evaluating tectonic models and developing seismic sources. Data will serve the specific needs of the program and will be available for any site specific evaluations that the NRC may later require.

4) Evaluation and selection seismic wave attenuation models applicable to the Eastern United States.

5) Assess decision methodologies and provide technical input to the Staff's decision process with respect to comparative evaluations of seismic hazard among sites.

6) Coordination, data transfer, and technology transfer within the program and with external groups, to be accomplished primarily through a series of workshops, a technical symposium and a referred technical publication.

The work will be based on existing geological, geophysical, and seismological data, either published or existing in files. Original data collection is not planned. As the program progresses during the first year, an evaluation will be made of the need for additional investigations that could have a high likelihood of significantly reducing uncertainty in the results. At that time, a follow-on work scope will be developed consistent with resolving issues that are identified as being particularly influential on the results.

SUMMARY

The EPRI program will involve several contractors working in parallel to compile a data base and perform tectonic evaluations. Data compilation will be carried out by as many as five contractors, each worksing in a specified geographic subregion of the Eastern United States. Following data compilation, each contractor will form an expert team consisting of a minimum of a geologist, a geophysicist and a seismologist. Two additional teams consisting of university-based experts will be added at this point resulting in a total of seven teams. The contractors' expert teams will perform tectonic evaluations leading to the development of probabilistic seismic sources for input to the seismic hazard computations. Workshops will be the key method of exchanging data and interpretations among expert teams. Concensus interpretations among teams will not be required, but common understanding of the competing interpretations and the physical basis for them will be sought. Close coordination will be maintained with NRC.

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